Structure and decay of the most neutron-rich nuclei, 115≤A≤138 and the role of their decay properties in r-process nucleosynthesis

W. B. Walters, University of Maryland College Park

Let me start by thanking the organizers of the meeting for the invitation to speak this morning, and with an acknowledgement of the support of the U. S. Department of Energy for this research through the University of Maryland.

Today, I will review studies of the decay of neutron-rich nuclides with which I have been involved for about a decade.

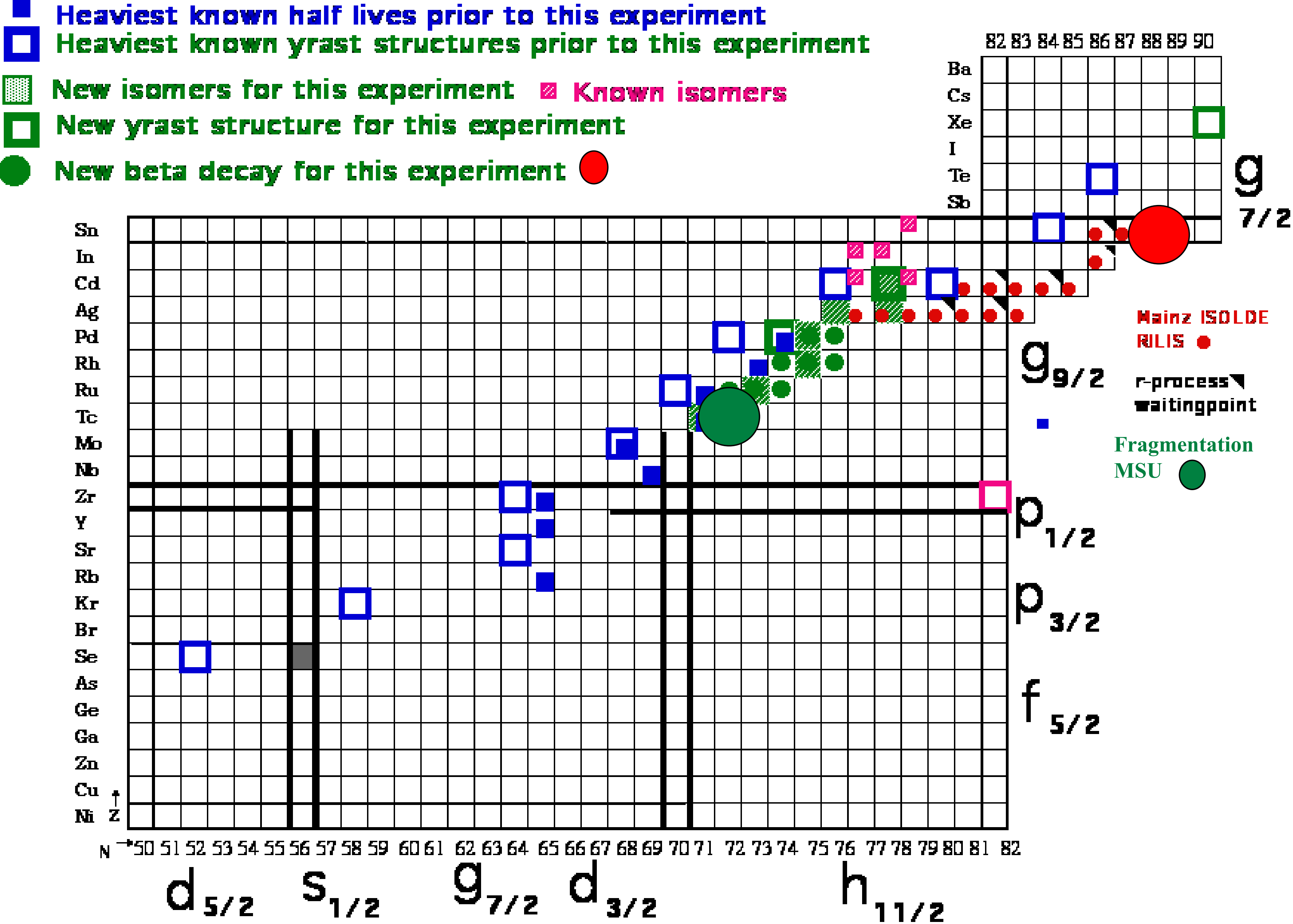
Work has been performed in collaboration with the K.-L. Kratz group in Mainz, along with the ISOLDE Collaboration at CERN for nuclides with 122≤A≤138

And, with Paul Mantica and Hendrick Schatz at MSU for nuclides with 115≤A≤126

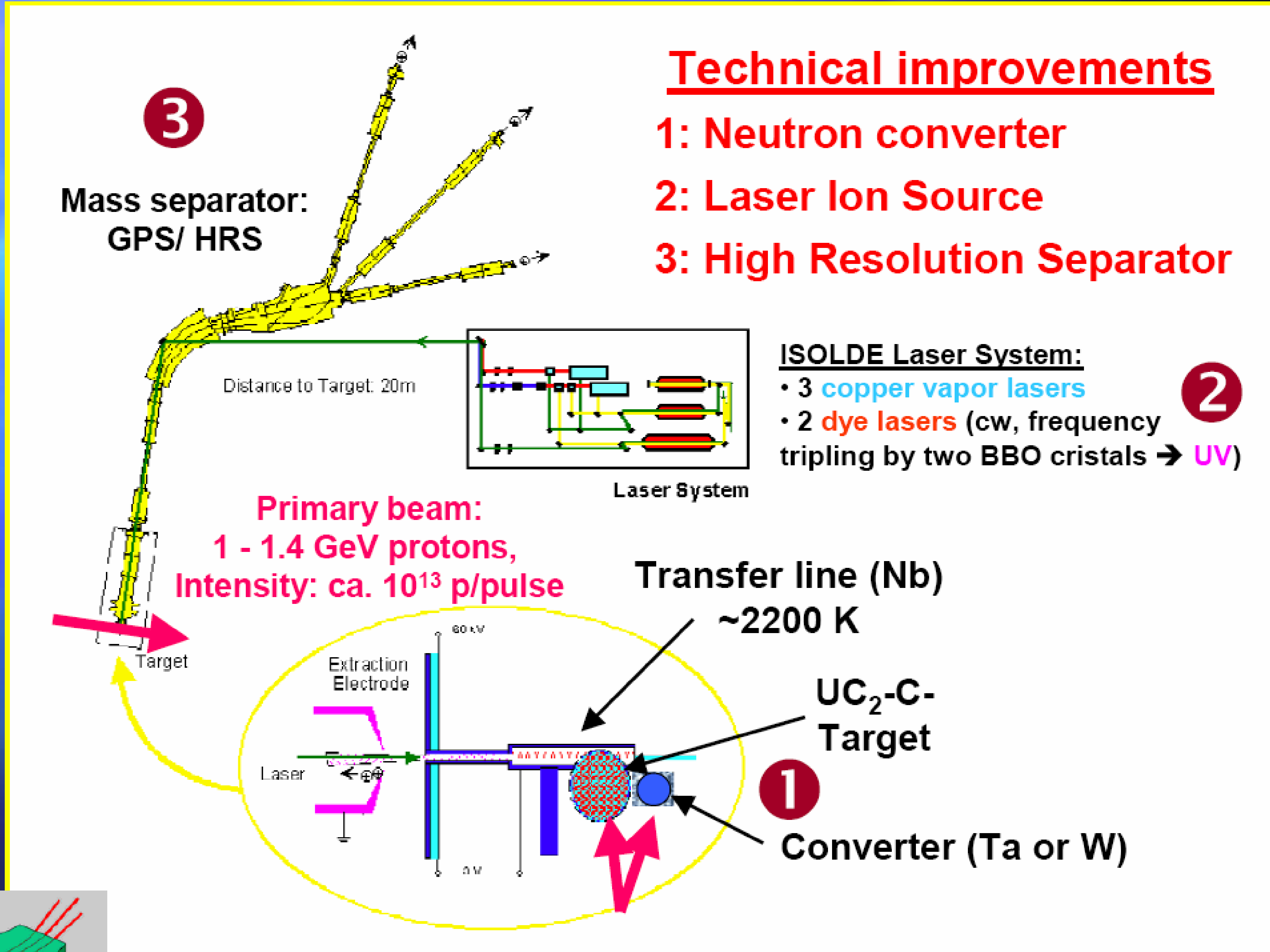
This talk will be a mixture of nuclear structure and decay along with the use of these data in various r-process nucleosynthesis calculations

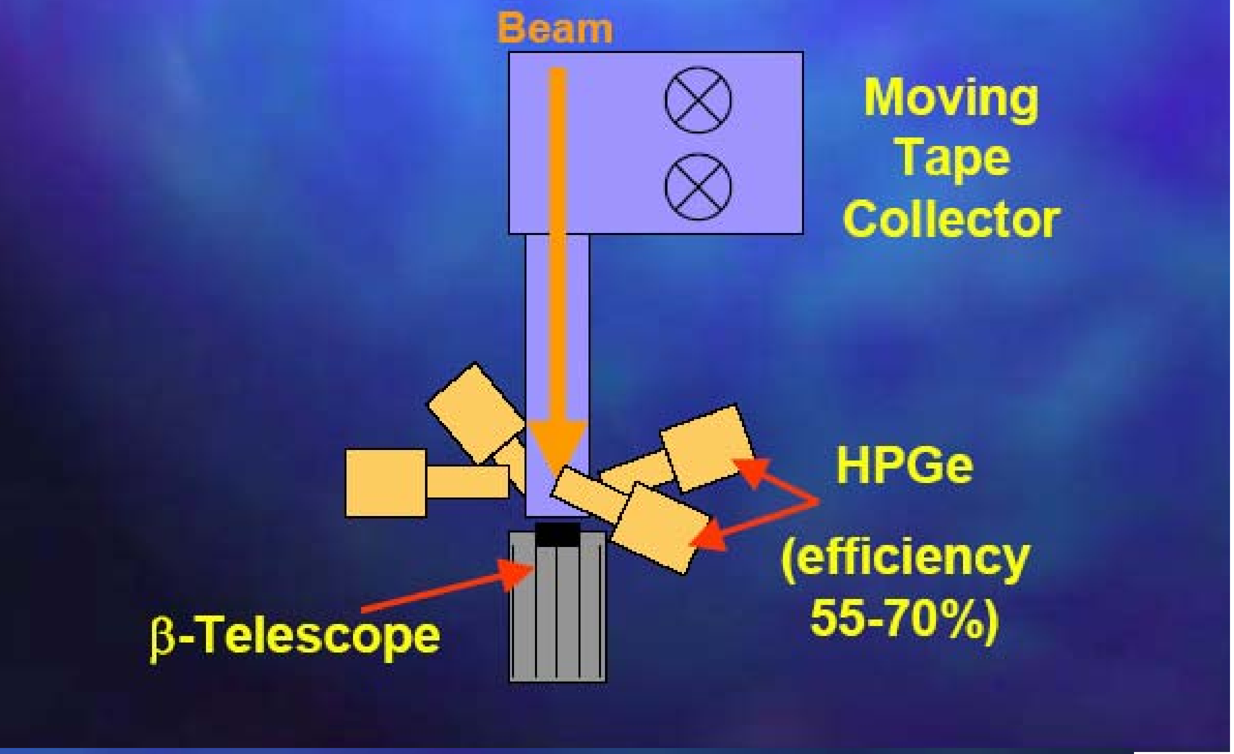
1. Technical details of the studies at ISOLDE
2. New Physics at ISOLDE
3. Technical details at MSU
4. New physics at MSU
5. The waiting-point idea in r-process nucleosynthesis
6. Dependences on neutron density, neutron binding, and half life
7. r-process paths and new data
8. Summary and conclusions

This is a meeting about “limits”, so in this talk, data and results will be presented for the decay of nuclides at the limits of what can (or has) been studied up to this point.

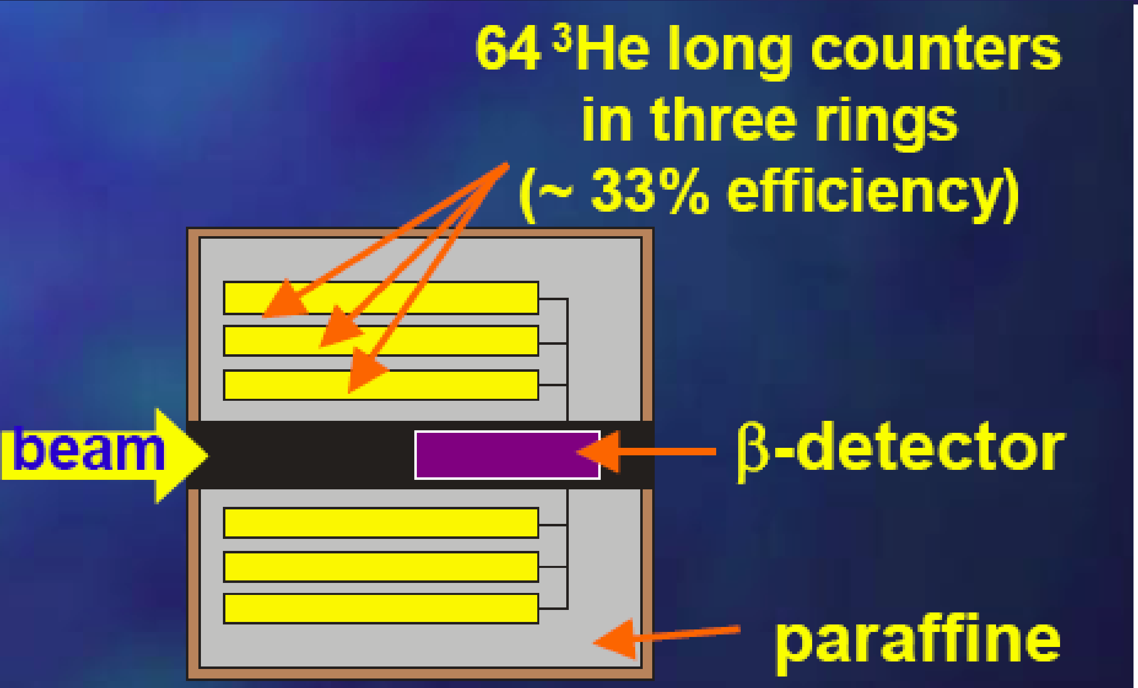


MSU1015: Decay of Rh-120 to levels of Pd-120


Technical improvements
1: Neutron converter
2: Laser Ion Source
3: High Resolution Separator
3
Mass separator:
GPS/ HRS
Distance to Target: 20m
Laser System
ISOLDE Laser System:
• 3 copper vapor lasers
• 2 dye lasers (cw, frequency tripling by two BBO cristals → UV)
2
Primary beam:
1 - 1.4 GeV protons,
Intensity: ca. 10^{13} p/pulse
Transfer line (Nb)
~2200 K
UC_2-C-
Target
1
Converter (Ta or W)
60 kV
Extraction
Electrode
Laser
Target
0 V



Mainz Microarray

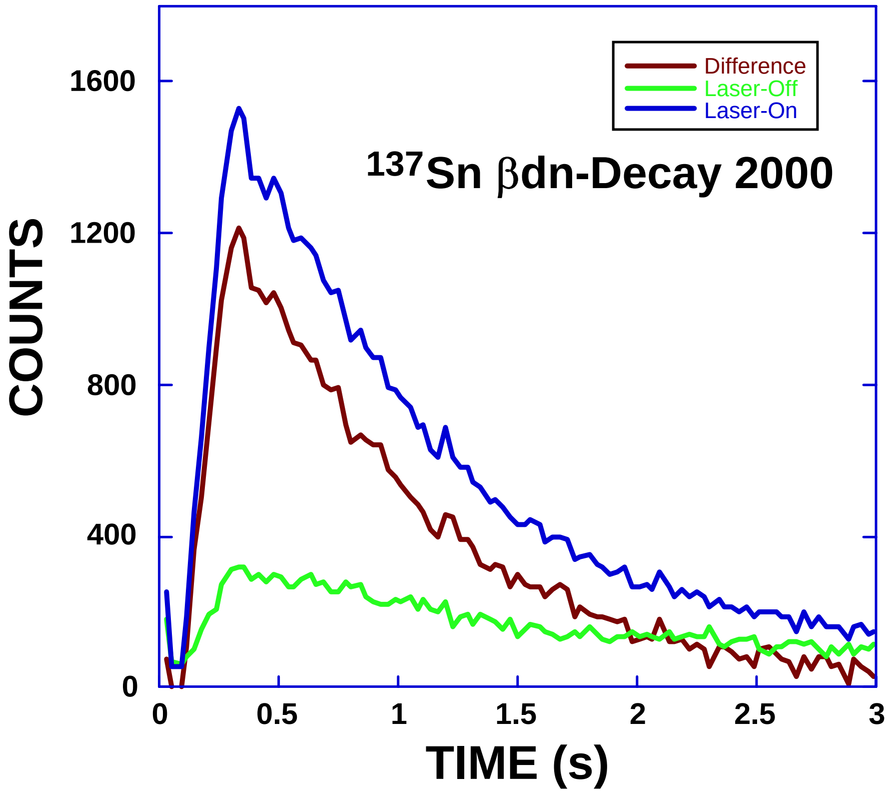


Mainz ^{3}He neutron detector

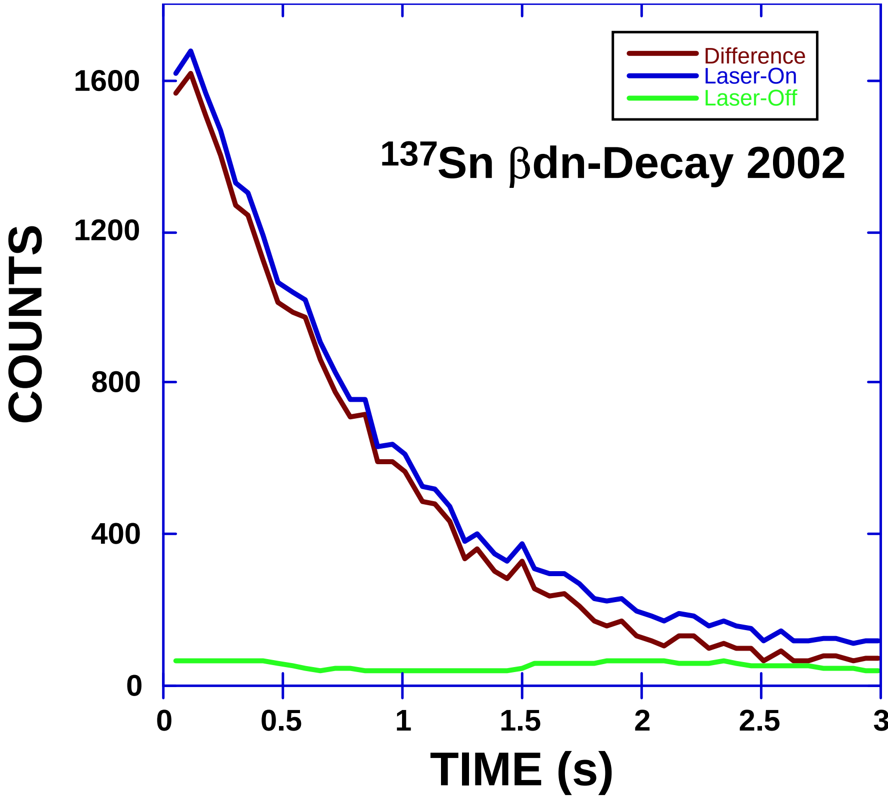
^{135}Sn decay

Laser on

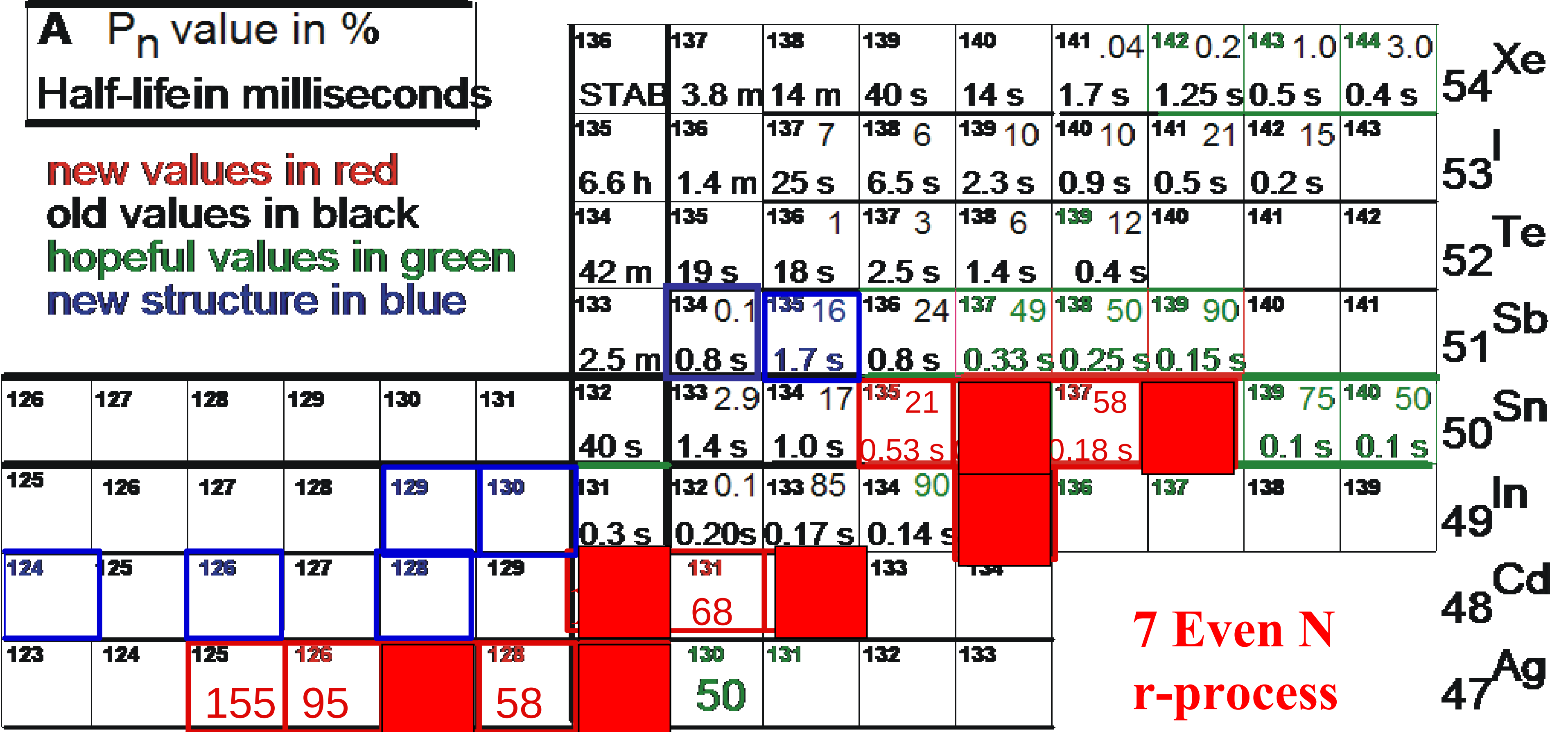
Laser off



COUNTS
1600
1200
800
400
0
0
0.5
1
1.5
2
2.5
3
TIME (s)
Difference
Laser-Off
Laser-On
^{137}Sn βdn-Decay 2000



COUNTS
1600
1200
800
400
0
0
0.5
1
1.5
2
2.5
3
TIME (s)
Difference
Laser-On
Laser-Off
^{137}Sn βdn-Decay 2002



7 Even N r-process waiting-point nuclei

Y. Jading et al., Nuclear Instruments and Methods B **126**, 76 (1997).

T. Kautzsch, W. B. Walters, and K.-L. Kratz, AIP Conference Series **447**, 1183 (1998).

M. Hannawald et al., Physical Review C **62**, 054301 (September 25, 2000).

I. Dillmann et al., European Physics. Journal A **13**, 281 ((March 2002).

T. Kautzsch et al., Physical Review C **54**, R2811-R-2814 (December 1996).

T. Kautzsch et al., European Physics Journal A, **9** 201-206 (October 2000).

J. Shergur et al., Physical Review C **65**, 034313 (March 2002).

A. Wöhr et al., Proc. 11th Workshop on Nuclear Astrophysics, Ringberg Castle, Feb. 2002.

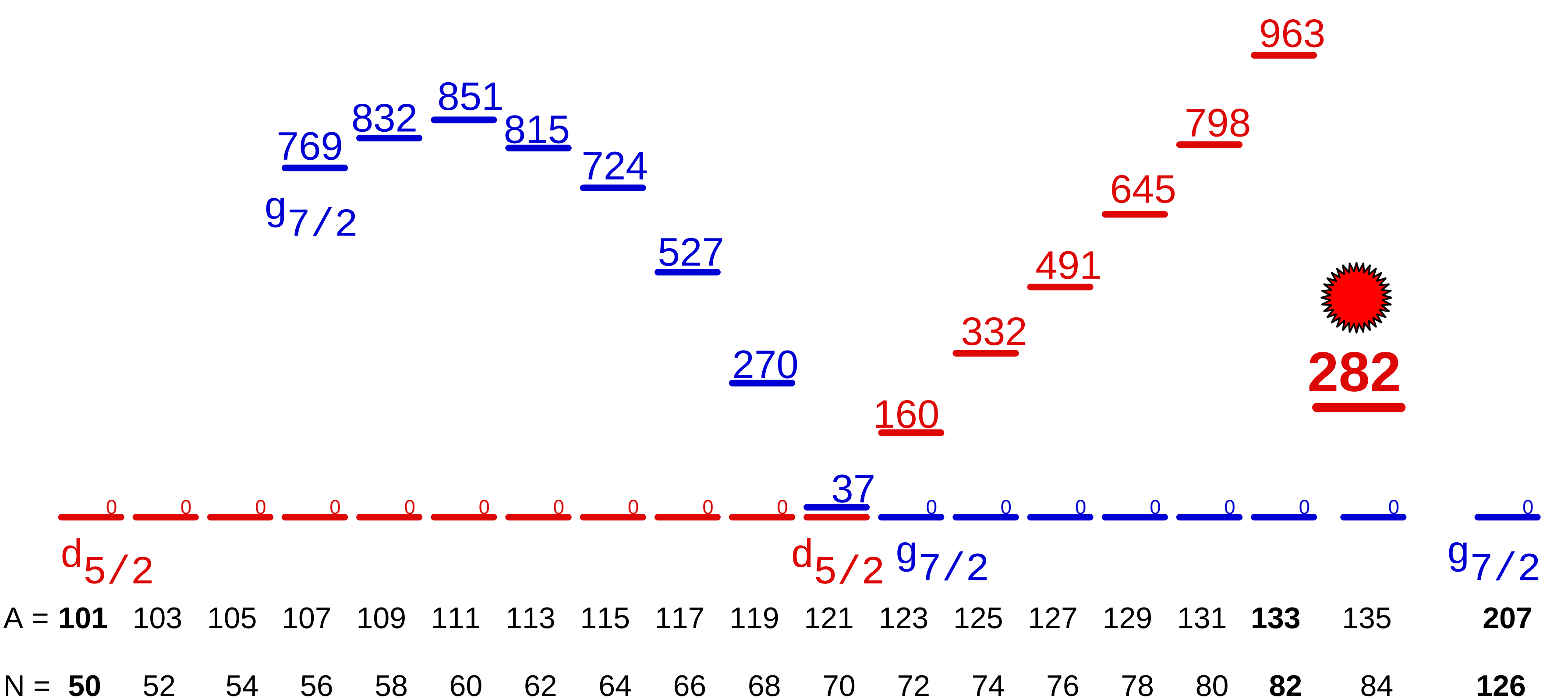
I. Dillmann et al., Phys. Rev. Lett. 91, 162503 (2003).

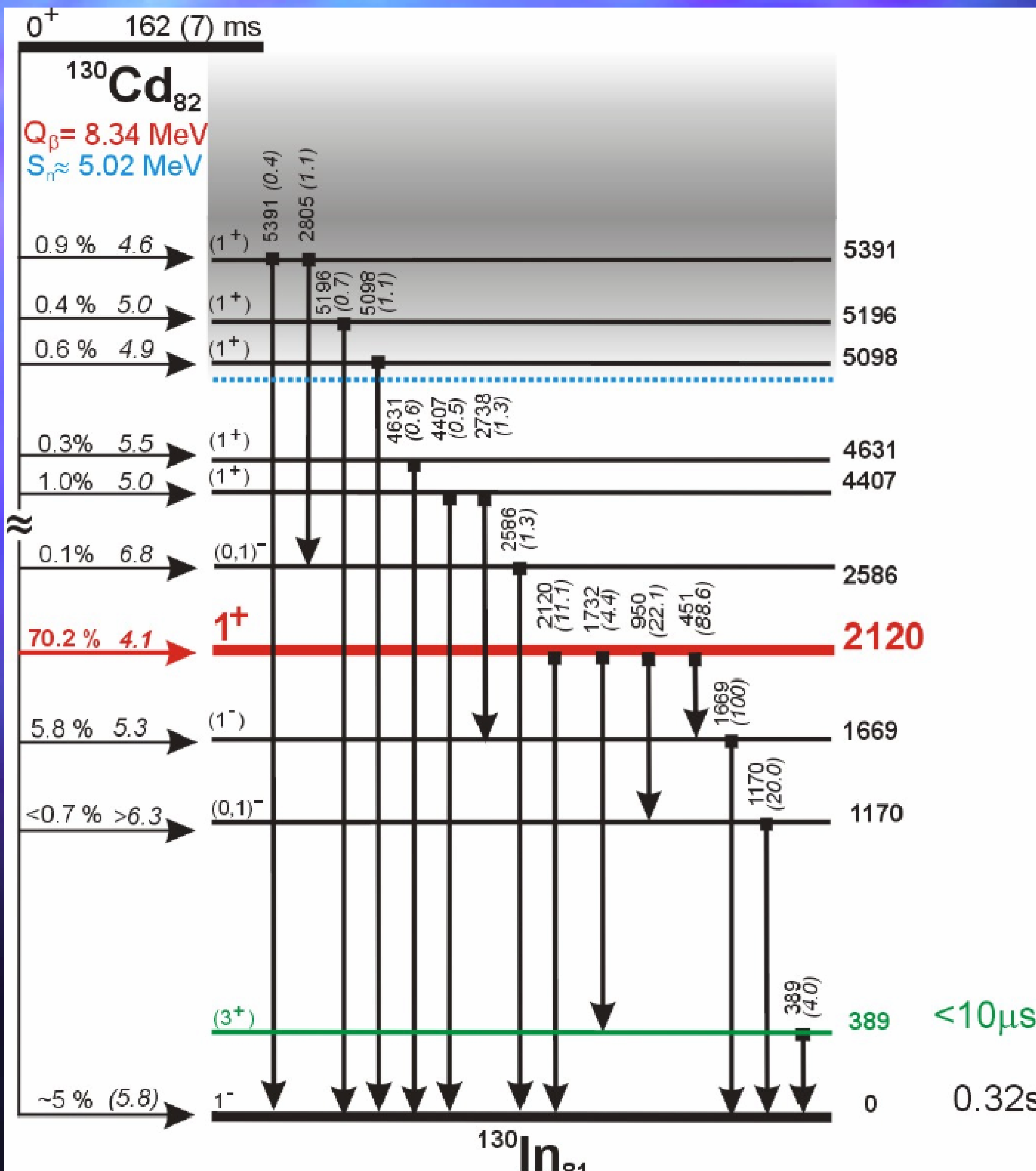
K.-L. Kratz, B. Pfeiffer, F.-K. Thielemann, and W. B. Walters, Hyperfine Interactions **129,** 185-221 (November 2000).

B. Pfeiffer, K.-L. Kratz, F.-K. Thielemann and W.B. Walters, Nuclear Physics A **693**, 282- 324 (October 8,2001)

Monopole shift in odd-mass Sb nuclides.

This sudden narrowing of the $g_{7/2}$ -- $d_{5/2}$ gap is attributed to the effects of the "neutron skin" just beyond ^{132}Sn



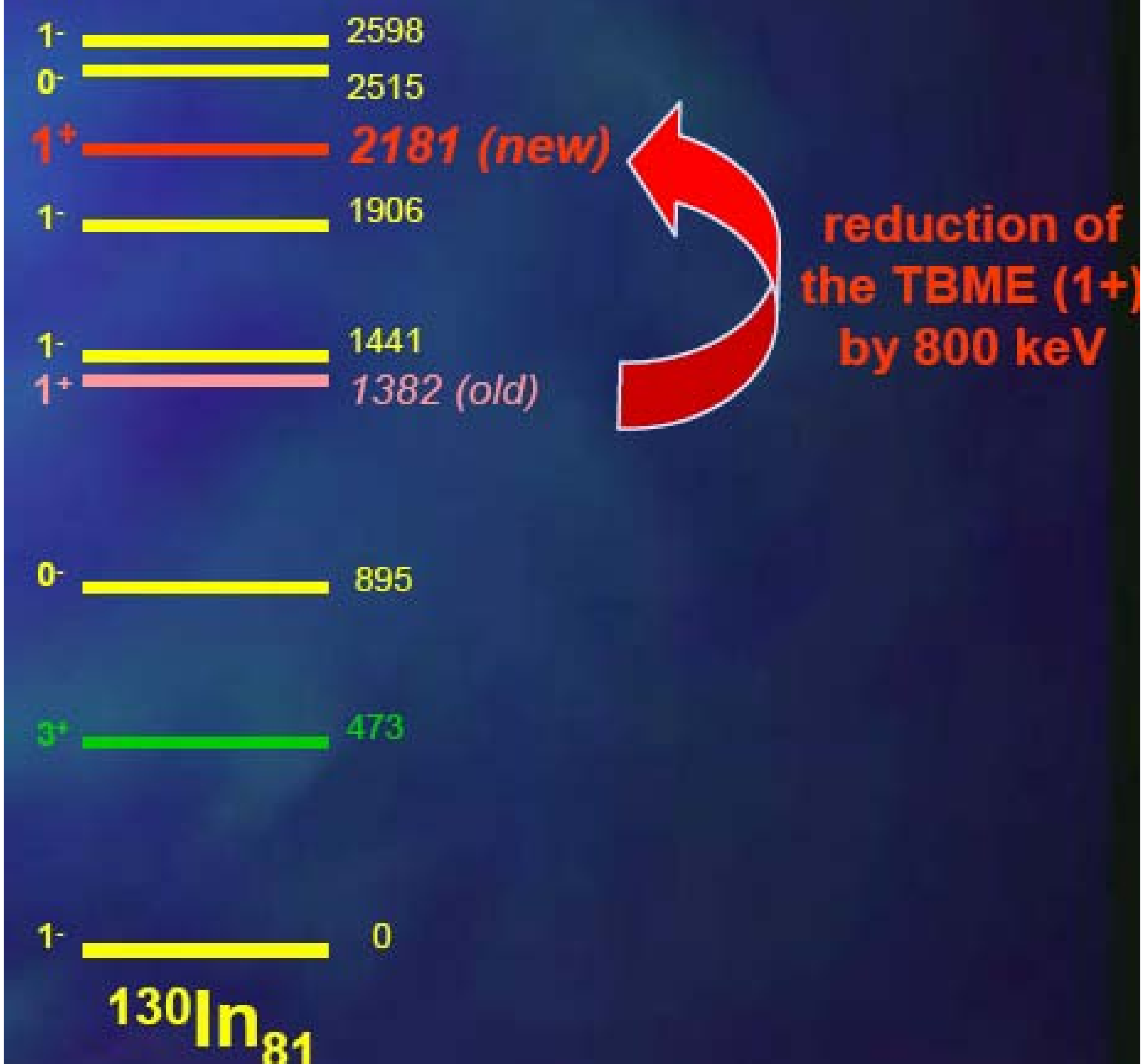


^{130}Cd is THE key "waiting-point" nuclide that is largely responsible for the peak in the elemental abundance curve at A = 130.

It can be called the "gate-keeper for the r-process".

OXBASH

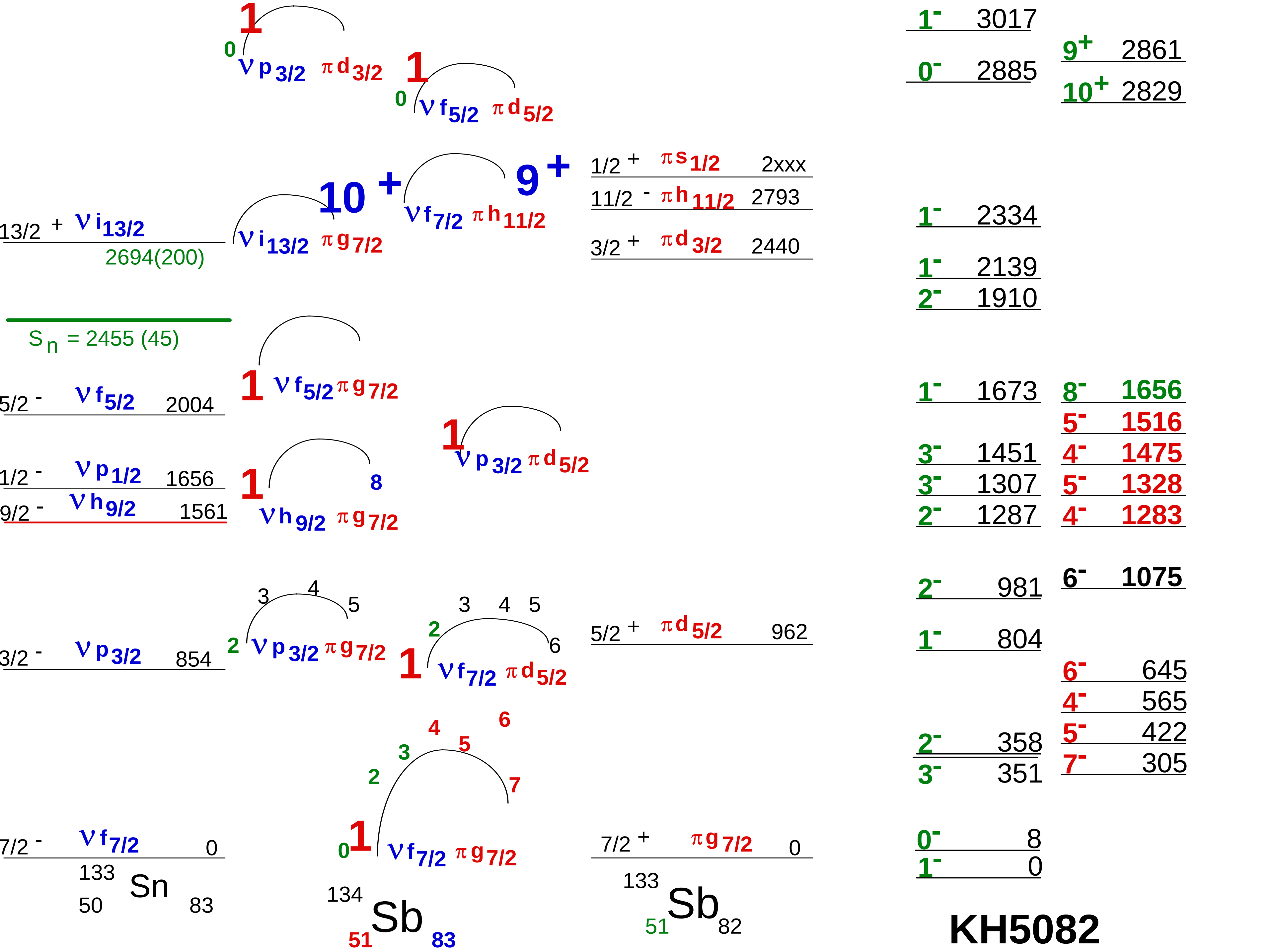
(B.A. Brown, Oct. 2003)



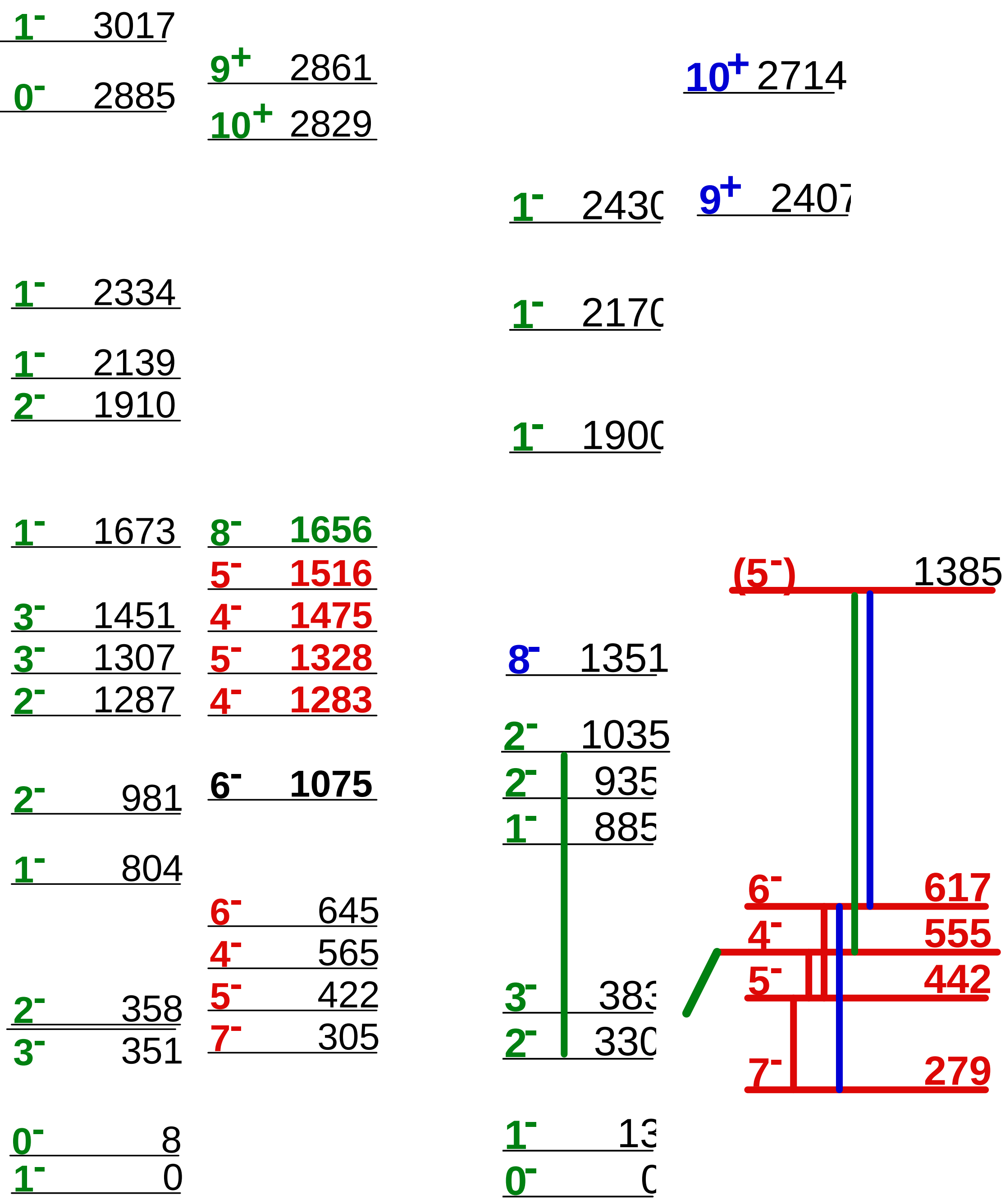
Mass model predictions

	Q_β
Hilf et al. (*GTNM*, 1976)	7.57 MeV
Möller et al. (*FRDM*, 1995):	7.43 MeV
Aboussir et al. (*ETFSI*, 1995):	7.87 MeV
Duflo & Zuker (1995)	7.56 MeV
Dobaczewski et al. (*HFB/SkP*, 1996):	8.93 MeV
Pearson et al. (*ETFSI-Q*, 1996):	8.30 MeV
Audi & Wapstra (*Mass Eval.*, 1997):	8.50 MeV
Goriely et al. (*HFBCS*, 2001)	7.00 MeV
Samyn et al. (*HFB*-2, 2002)	7.64 MeV
Brown et al. (*local OXBASH,* 2003):	8.75 MeV

$Q_\beta = 8344$ keV



13/2 + ν i13/2
2694(200)
Sn = 2455 (45)
5/2 - ν f5/2 2004
1/2 - ν p1/2 1656
9/2 - ν h9/2 1561
3/2 - ν p3/2 854
7/2 - ν f7/2 0
133 50 Sn 83
ν p3/2 π d3/2
ν f5/2 π d5/2
10 + ν i13/2 π g7/2
9 + ν f7/2 π h11/2
ν f5/2 π g7/2
ν p3/2 π d5/2
ν h9/2 π g7/2
ν p3/2 π g7/2
ν f7/2 π d5/2
ν f7/2 π g7/2
134 51 Sb 83
1/2 + π s1/2 2xxx
11/2 - π h11/2 2793
3/2 + π d3/2 2440
5/2 + π d5/2 962
7/2 + π g7/2 0
133 51 Sb 82
1- 3017
0- 2885
9+ 2861
10+ 2829
1- 2334
1- 2139
2- 1910
1- 1673
8- 1656
5- 1516
3- 1451
4- 1475
3- 1307
5- 1328
2- 1287
4- 1283
2- 981
6- 1075
1- 804
6- 645
4- 565
2- 358
5- 422
3- 351
7- 305
0- 8
1- 0
KH5082



Korgul et al., 2002

High-spin fission

Sn-135 βdn decay

Sn-134 beta decay

KH5082

^{120}Rh Production Details

Primary Beam: $^{136}Xe^{49+}$, 120 MeV/A
Average Beam Current: 1.5 pnA
Production Target: ^{9}Be, 188 mg/cm^2
Wedge: plastic scintillator + Kapton
A1900 $B\rho_{1,2}$ = 3.95970 Tm
A1900 $B\rho_{3,4}$ = 3.83970 Tm

Layout of the NSCL Experimental Facilities

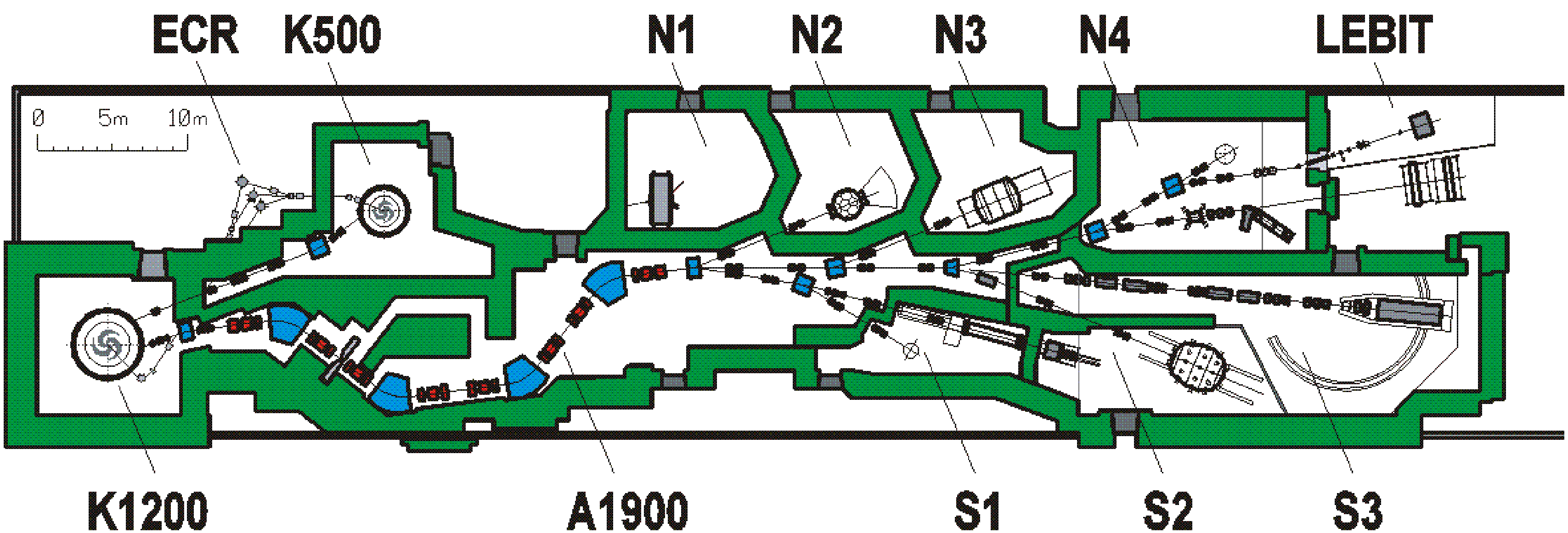
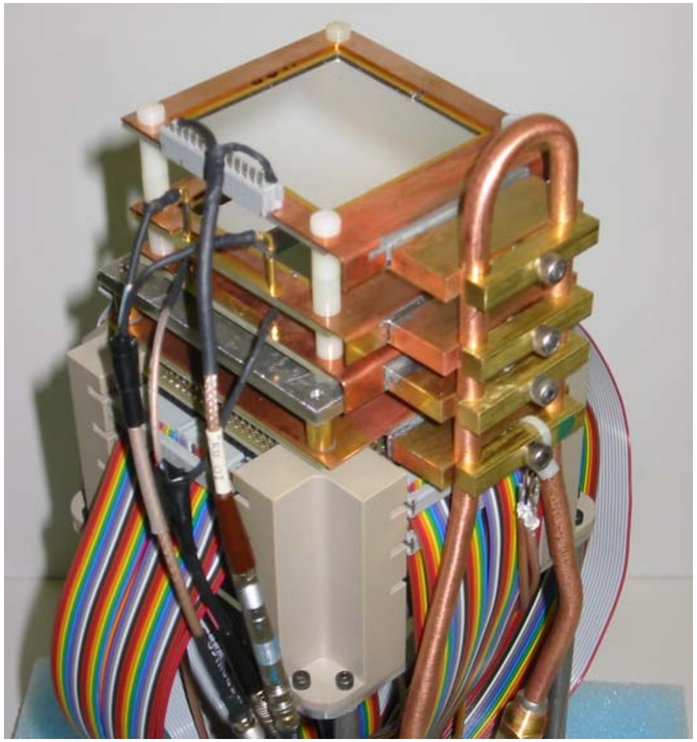
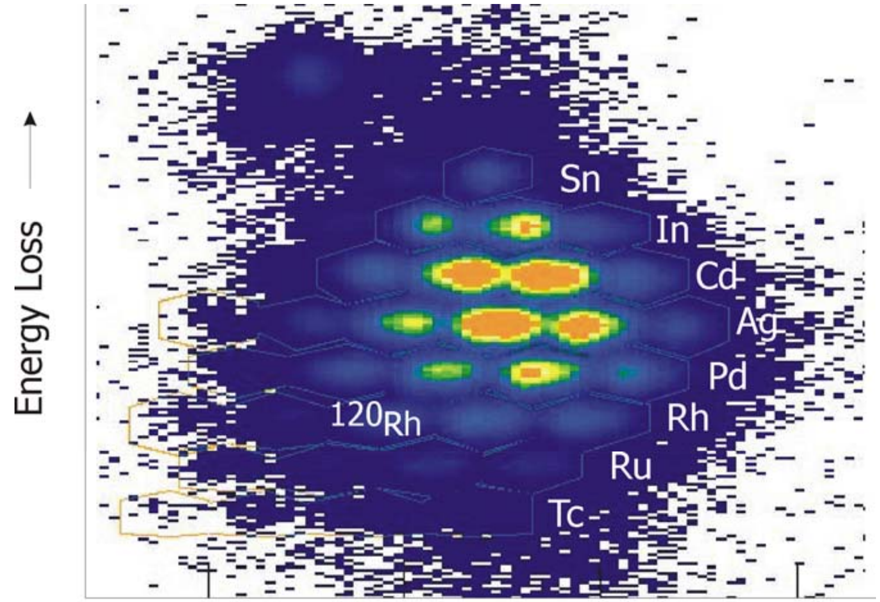


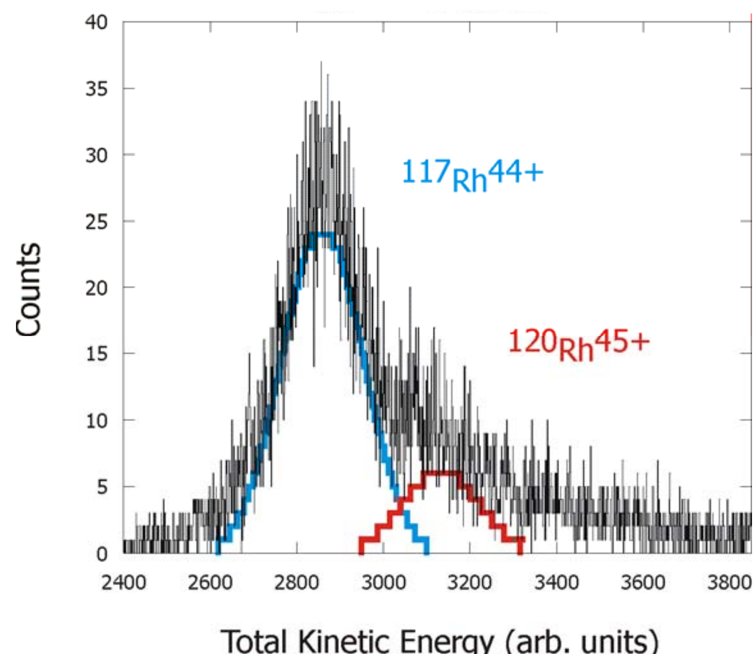
Photo of the BCS

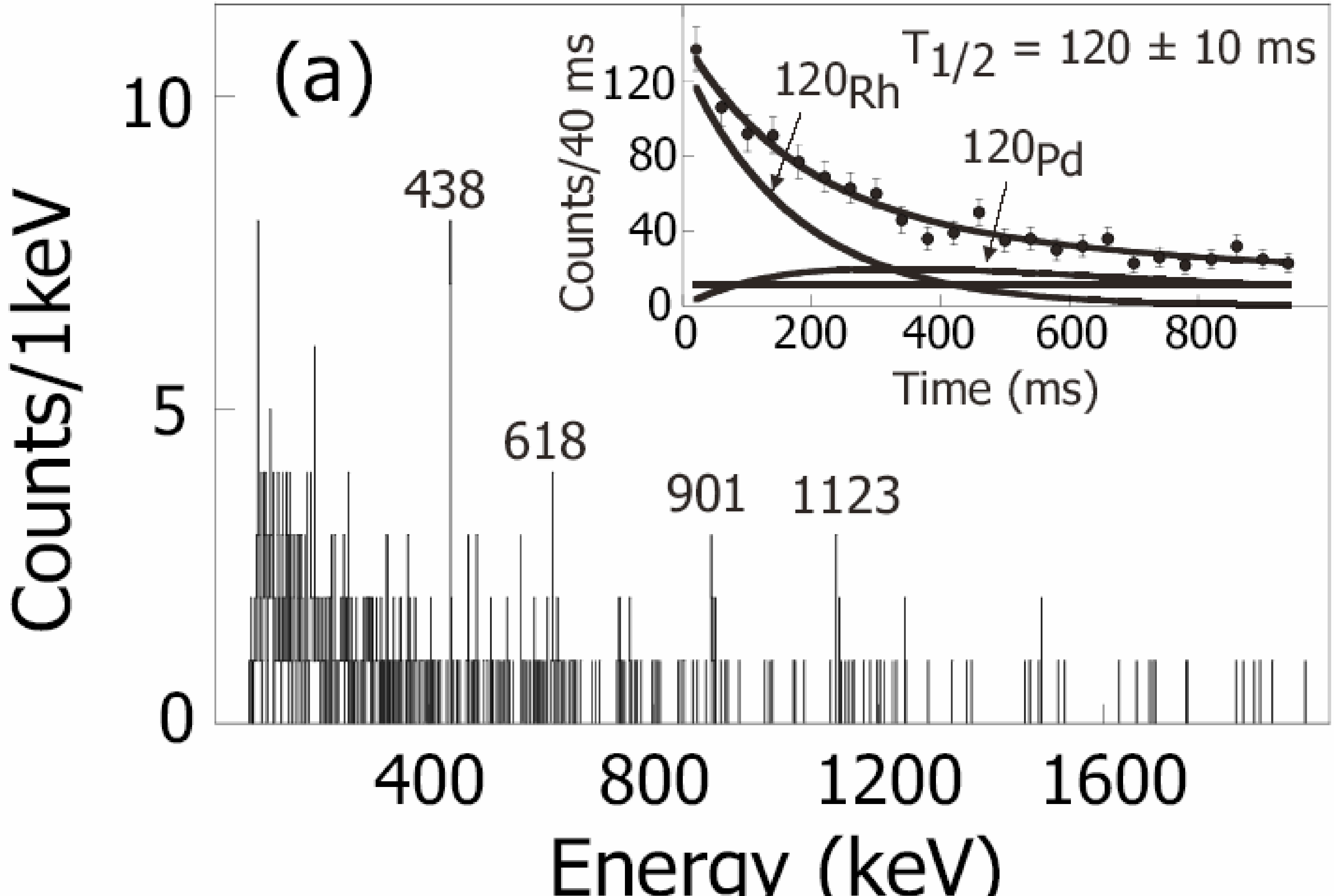


The beta-counting system at MSU was developed by Paul Mantica and his group and is a fantastic device for the correlation of beta decay with gamma rays in the SEGA array.

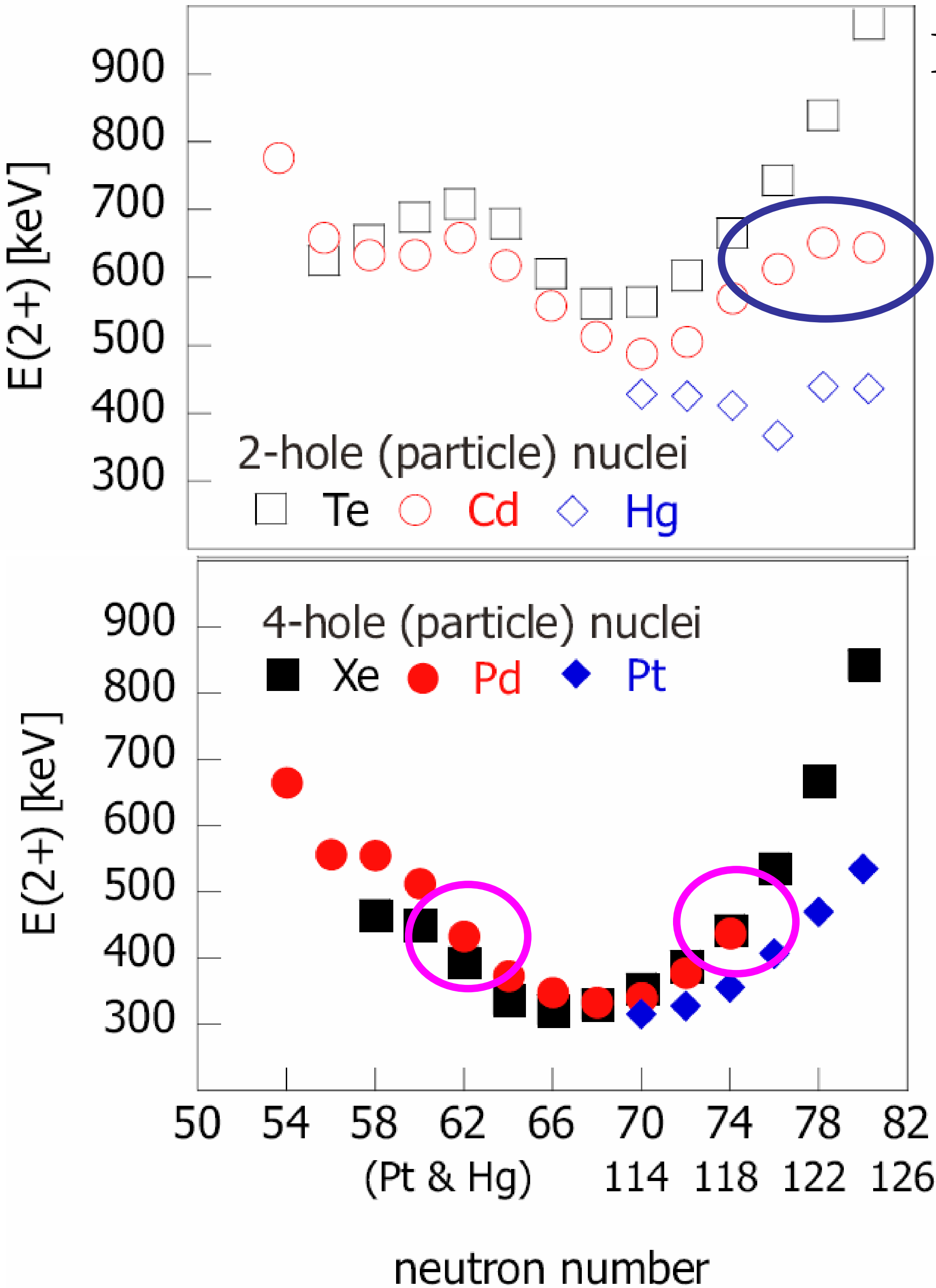
^{120}Rh PID Spectrum





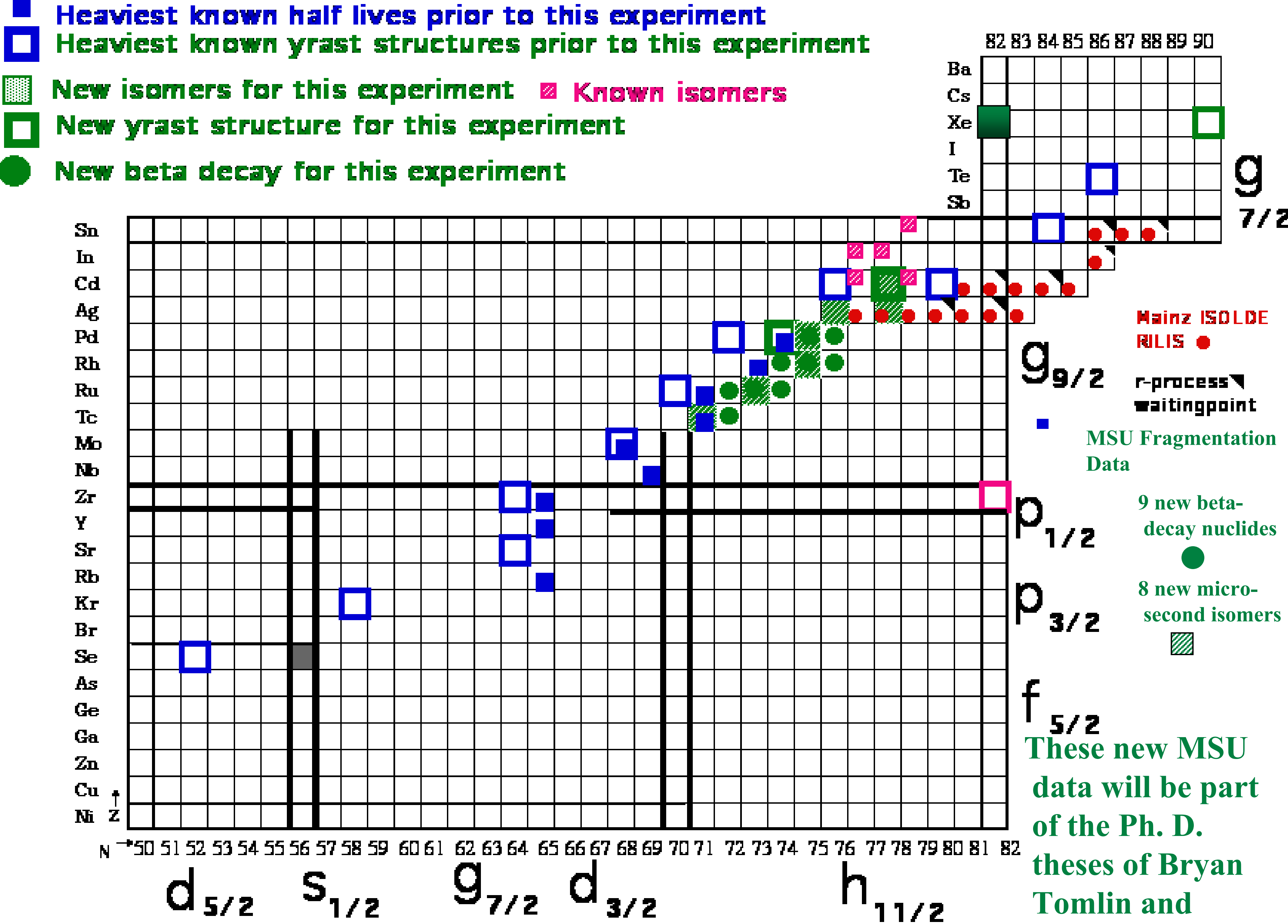


(a)
Counts/1keV
10
5
0
438
618
901
1123
400
800
1200
1600
Energy (keV)
$T_{1/2}$ = 120 ± 10 ms
Counts/40 ms
120
80
40
0
120Rh
120Pd
0
200
400
600
800
Time (ms)



Early discovery at ISOLDE was the "non-bosonic" behavior of the 2+ levels in the heavy even-even Cd nuclides, ^{126}Cd and ^{128}Cd.

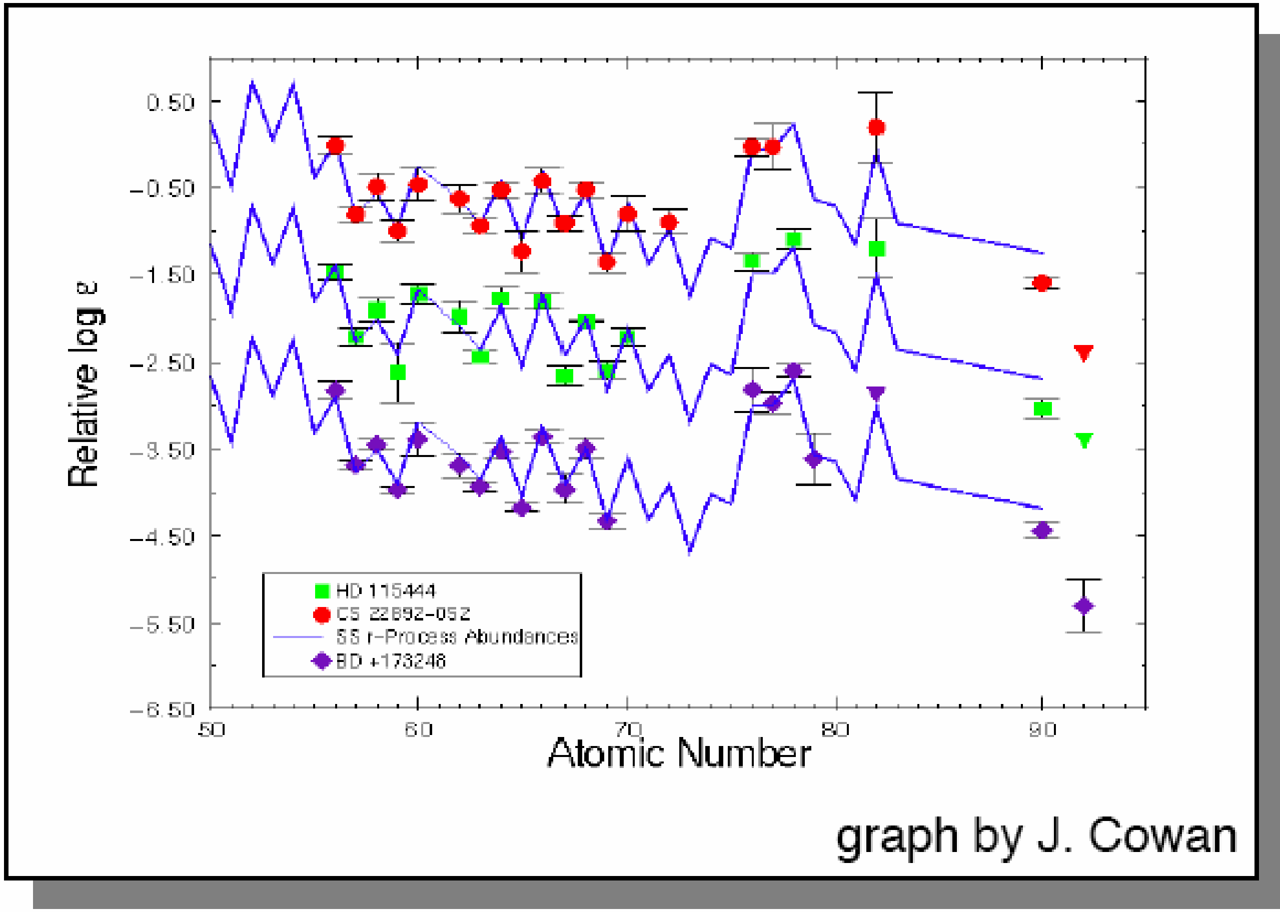
In contrast, the new data from MSU for ^{120}Pd show just the opposite, excellent agreement with a 1996 IBM-2 calculation, and virtually identical energies for the 2+ levels in isotonic ^{128}Xe and isotopic ^{108}Pd



These new MSU data will be part of the Ph. D. theses of Bryan Tomlin and Fernando Montes.

MSU1015: Decay of Rh-120 to levels of Pd-120

What role do these data play in r-process nucleosynthesis calculations?



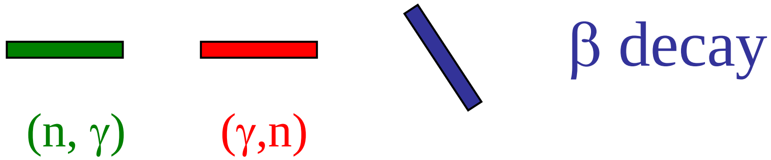
The dark blue line shows the solar r-process abundances.

Astronomy motivation: Relative elemental abundances in old halo stars (low Fe/H ratio) nearly identical to the observed solar abundances.

Such data provide fuel to the debate over " a single r-process or "2 r-processes", or "many r-processes".

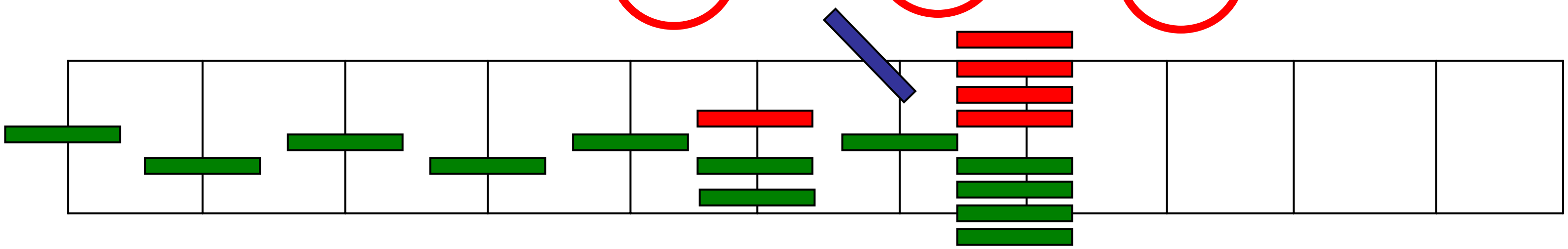
These particular data strongly support the notion of a single r-process for elements above A = 138

Now, I want to describe some details about the (γ,n) = (n, γ) equilibrium that show where and how nuclear structure and decay properties on nuclei play a role in r-process movement.



S_n = 2.5 for $^{104}Rb_{67}$…the process moves on.

Kr half-lives 104 48 23 15 9 5 ms.



S_n =	5.0	2.3	4.5	2.1	4.3	1.9	4.1	1.3	3.4	0.9	2.5
$_{36}Kr$	98	99	100	101	102	103	**104**	105	106	107	108
N =	62	63	64	65	66	67	68	69	70	71	72

Waiting points always have even neutron numbers.

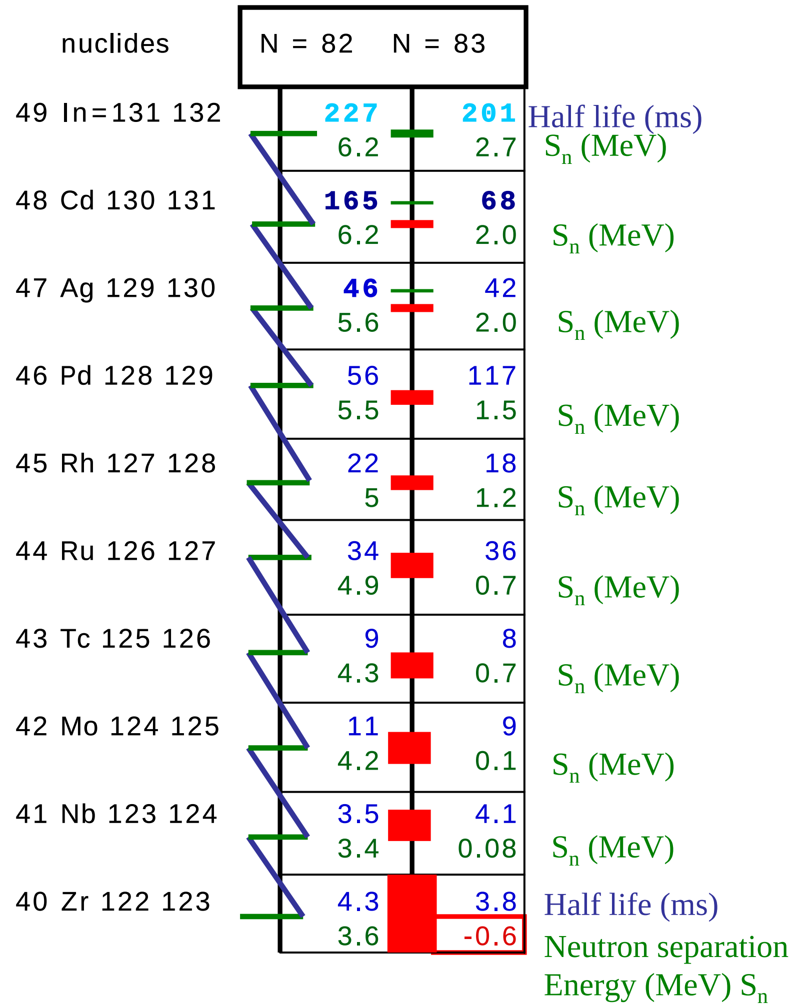
As the neutron density increases, the waiting point will move to 106 and 108 and so on, until the drip line is reached.

The N = 82 closed shell poses a particular barrier to the neutron-capture process.

In this model, ^{123}Zr is unbound and decay is necessary to move on.

Indeed, up through ^{127}Ru, the neutron separation energies are below 1 MeV and capture of additional neutrons will only occur under the highest neutron densities.

P. Möller, J. R. Nix, and K.-L. Kratz, ADNDT 66, 131(1997).



Conclusion: **The critical values from nuclear structure and decay measurements that are needed are half-lives and neutron separation energies (masses).**

In the **“waiting-point” model,** the observed abundances of stable nuclides arise from material that is **“waiting”** to either decay or capture a neutron at the point where the high neutron density ends.

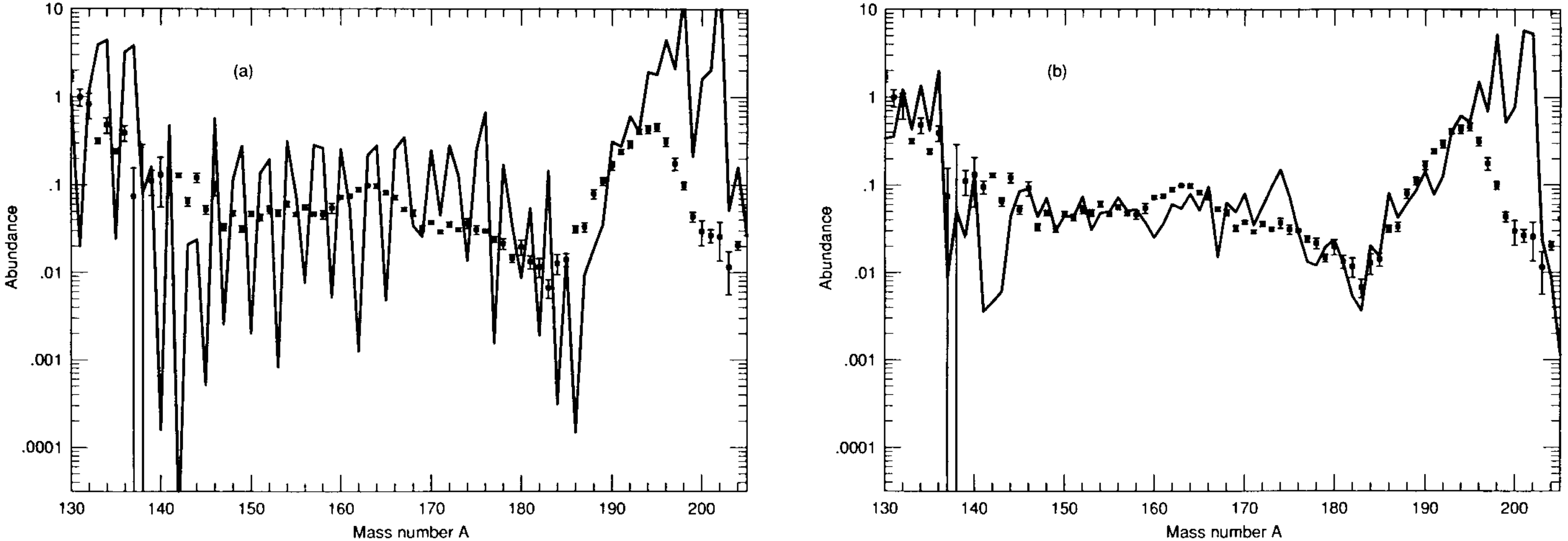


FIG. 9.—Best fit for r-abundances in the mass range $135 \leq A \leq 205$ for freeze-out conditions as in Fig. 8: (a) progenitor abundances before beta decay; (b) final abundances after beta decay and delayed neutron emission. The deviations for $A > 195$ again indicate the breakdown of the steady flow beyond the $N = 126$ neutron shell closure.

On the left are calculated abundances just at “freezeout”, and on the right are the abundances after decay, including beta-delayed neutron decay…..highlighting the importance of delayed neutron branching.

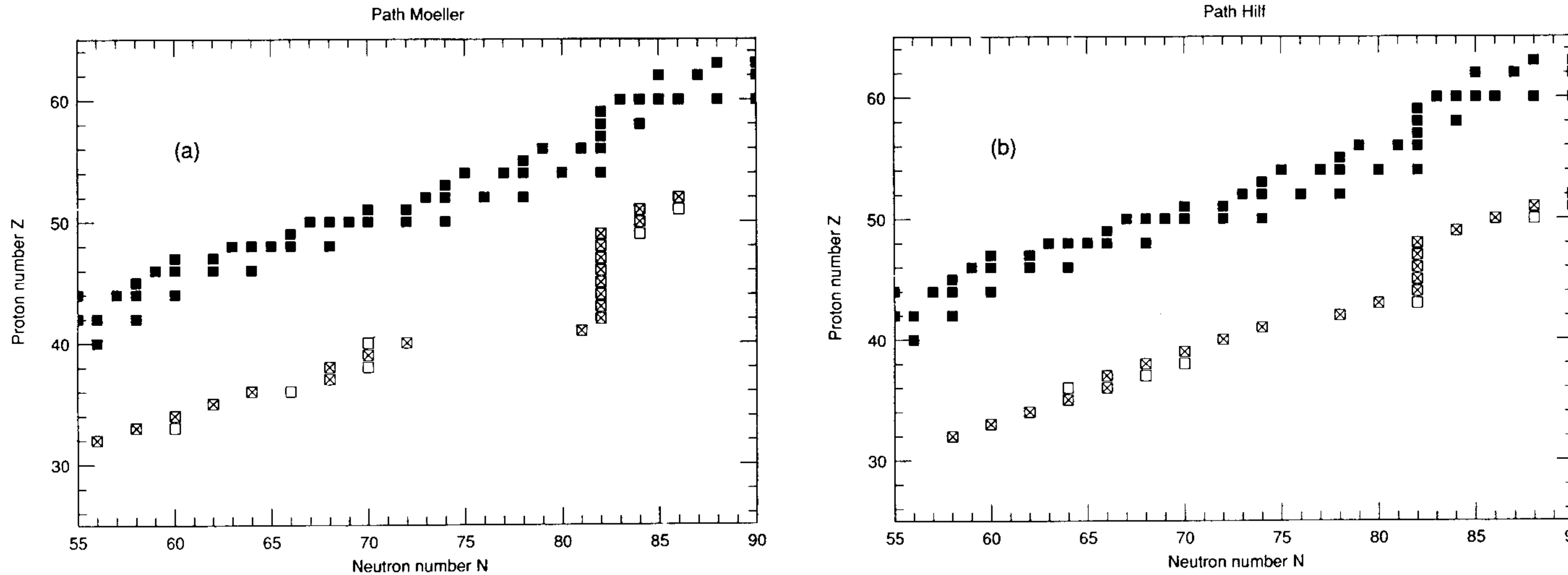
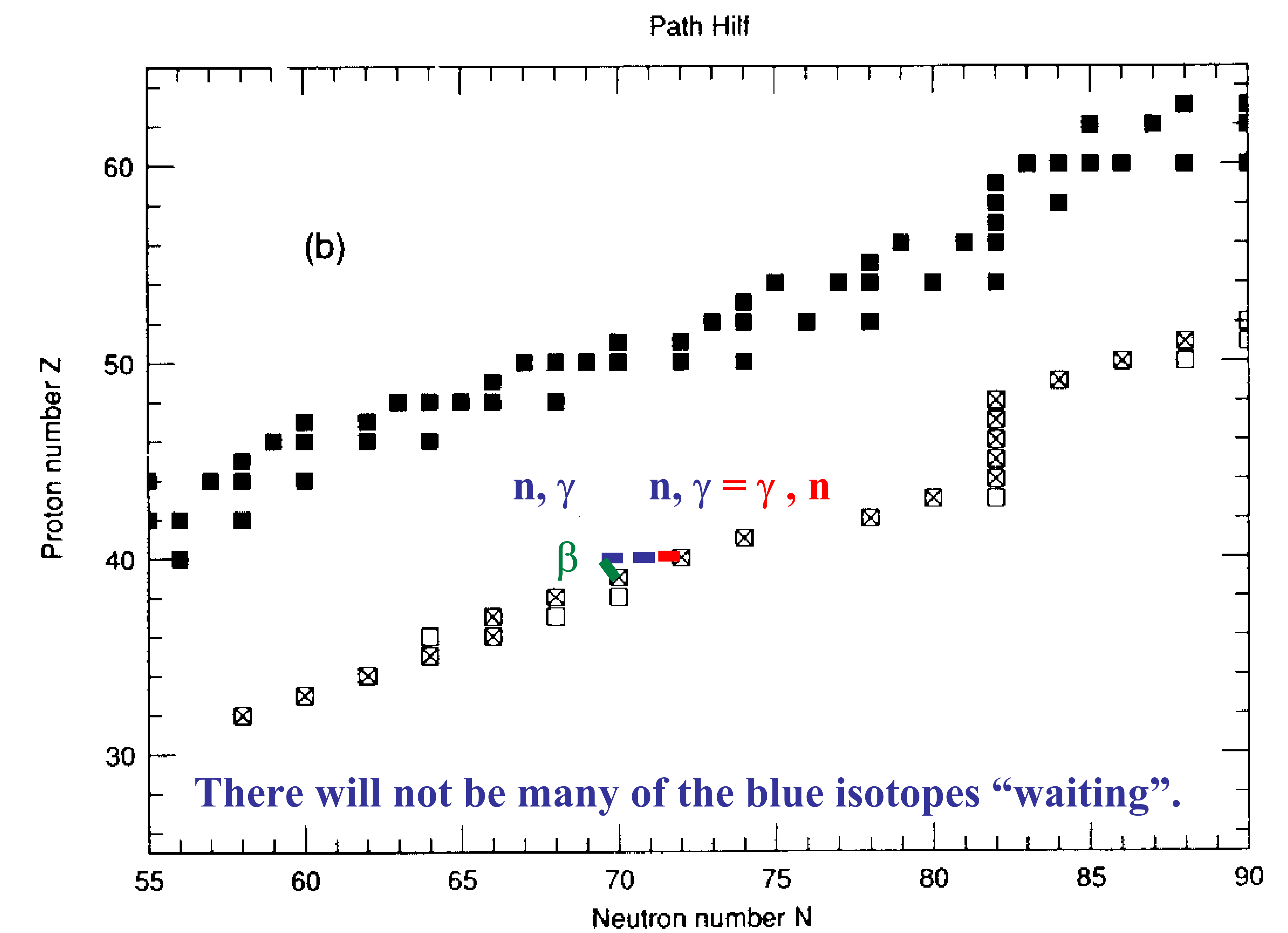
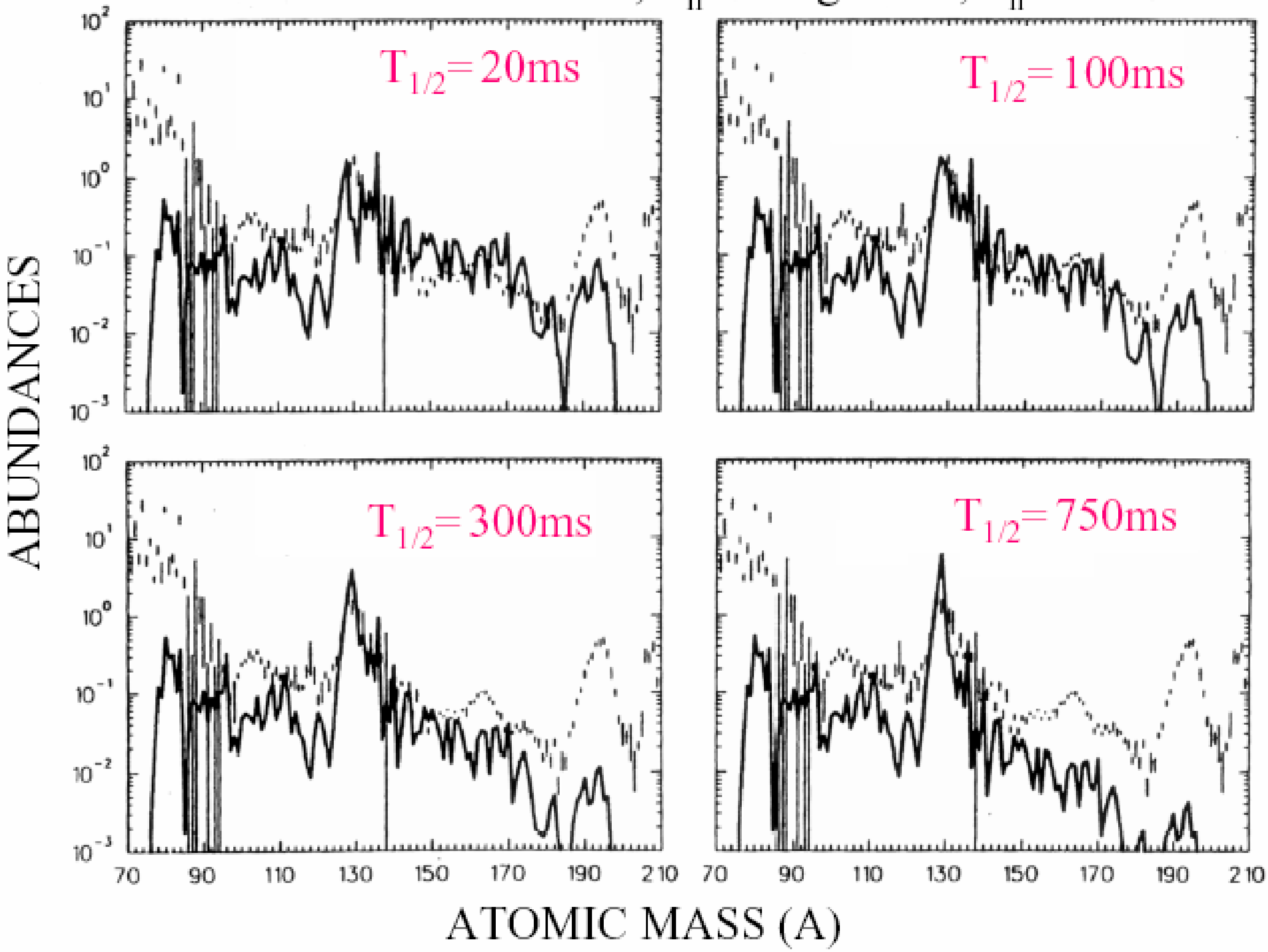


FIG. 11.—Schematic view of the r-process path in the $85 \simeq A \simeq 140$ mass region for freeze-out conditions ($T_9 = 1.2$, $n_n = 9.5 \times 10^{20}$ cm^{-3}) as in Fig. 10, containing nuclei with $B_n \simeq 2$ MeV. Shown are those isotopes with more than 10% population of each isotopic chain: (a) When using the mass model of Möller et al., one observes beyond $^{112}_{40}Zr_{72}$ a region of 9–10 masses where obviously no isotope with appropriate B_n value exists. Due to the strong shell strength in this mass model a sudden drop from $B_n \geq 3$ MeV to $B_n < 1$ MeV (see also Fig. 20) occurs close to the magic neutron number. (b) The Hilf et al. mass formula has obviously a smoother decrease in B_n values so that several isotopes exist in the r-process path between $A = 112$ and $A = 125$.

This is a plot similar to the one on the previous page showing the isotopes present at “freeze-out” under one set of astrophysical conditions, but using 2 different mass models. What is important is the fact that only even-N nuclides are present, and that they tend to be in pairs, with gaps.


Path Hilf
(b)
n, γ
n, γ = γ , n
β
There will not be many of the blue isotopes "waiting".
Proton number Z
Neutron number N
60
50
40
30
55
60
65
70
75
80
85
90

$T=1.35\ 10^9$ K, $n_n=10^{23}$g.cm^{-3} ; $\tau_n=1.86$s



The variable here is the half life of ^{130}Cd

The longer the half life, the more difficult and time consuming it is to get past ^{130}Cd.

Fig. 38. *Calculated abundance curve of the r-elements compared to solar values are given assuming various half-lives for the $^{130}Cd_{82}$ and $^{129}Ag_{82}$ waiting point nuclei. This calculation has been performed for a stellar temperature of T=1.35 10^9K, a neutron density of $d_n=10^{23}$cm^{-3}, and a time of τ_n=1.86s [174].*

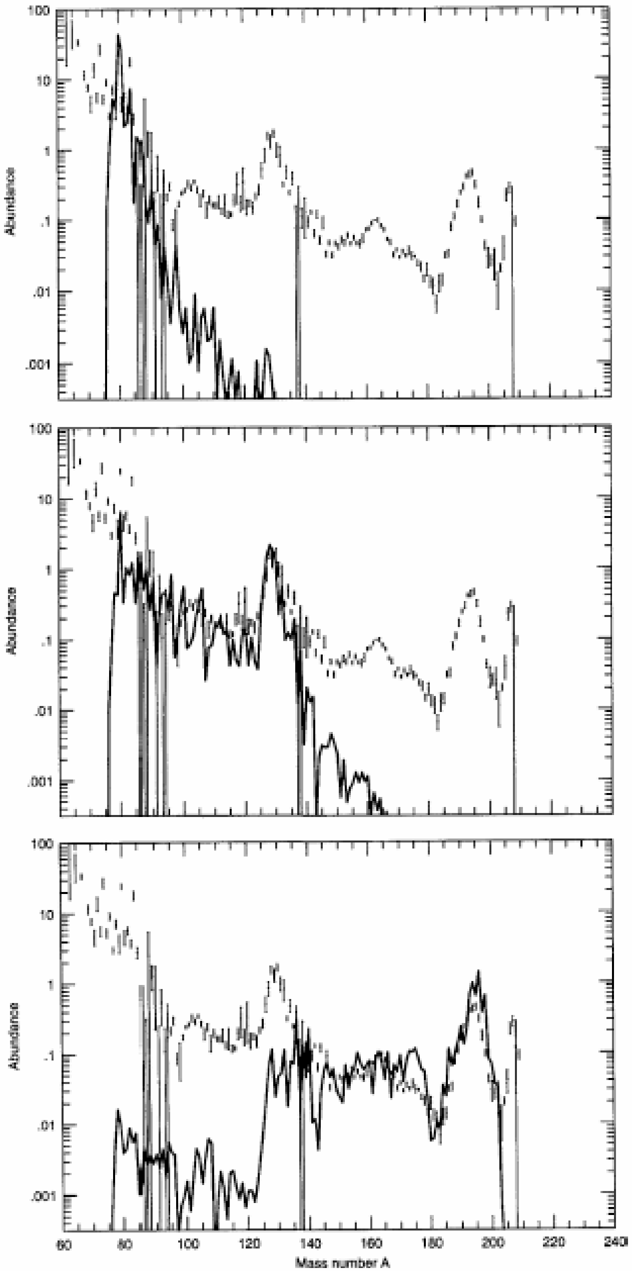


Fig. 2. Results of time-dependent r-process calculations with $n_n = 10^{20}$, 10^{22}, and 10^{24} g cm^{-3} at $T = 1.35 \times 10^9$ K for duration times τ of 1.2 (upper part), 1.7 (middle), and 2.1 s (lower part), respectively, in comparison with solar r-process abundances [34].

10^{20} n/cm^3

10^{22} n/cm^3

10^{24} n/cm^3

The variable here is the number of neutrons per cubic centimeter.

The higher the density, the heavier the nuclides that can be synthesized.

In order to make the Pt group peak nuclides, you can see that the density must exceed 10^{24} n/cm^3

In order to make Th and U, the densities need to be of the order of ~10^{27} n/cm$_3$.

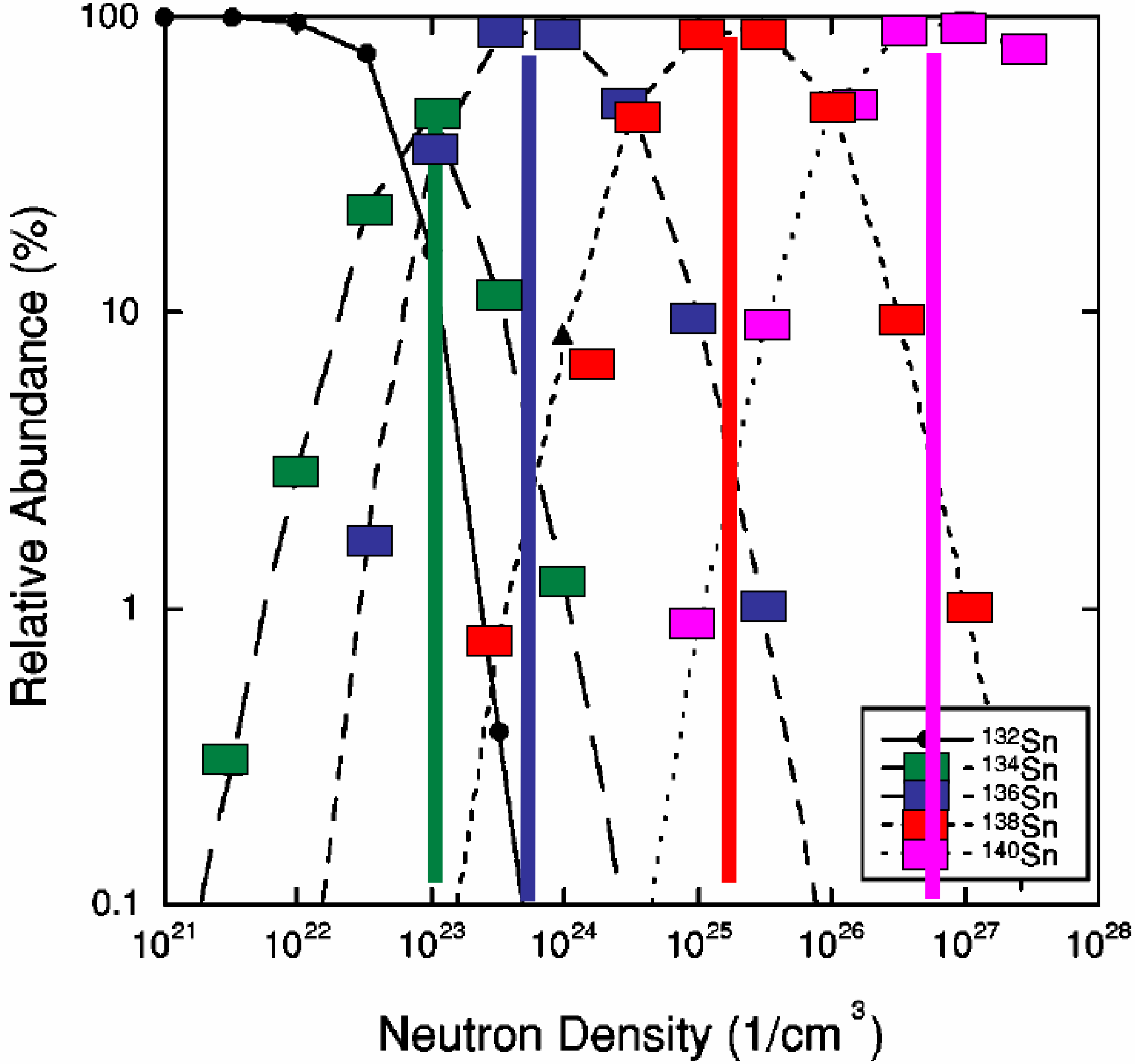


FIG. 11. Relative isotopic *r*-process abundances of Sn isotopes under freeze-out conditions ($T_9 = 1.35$) as a function of neutron density. For details, see text.

^{132}Sn 40 seconds

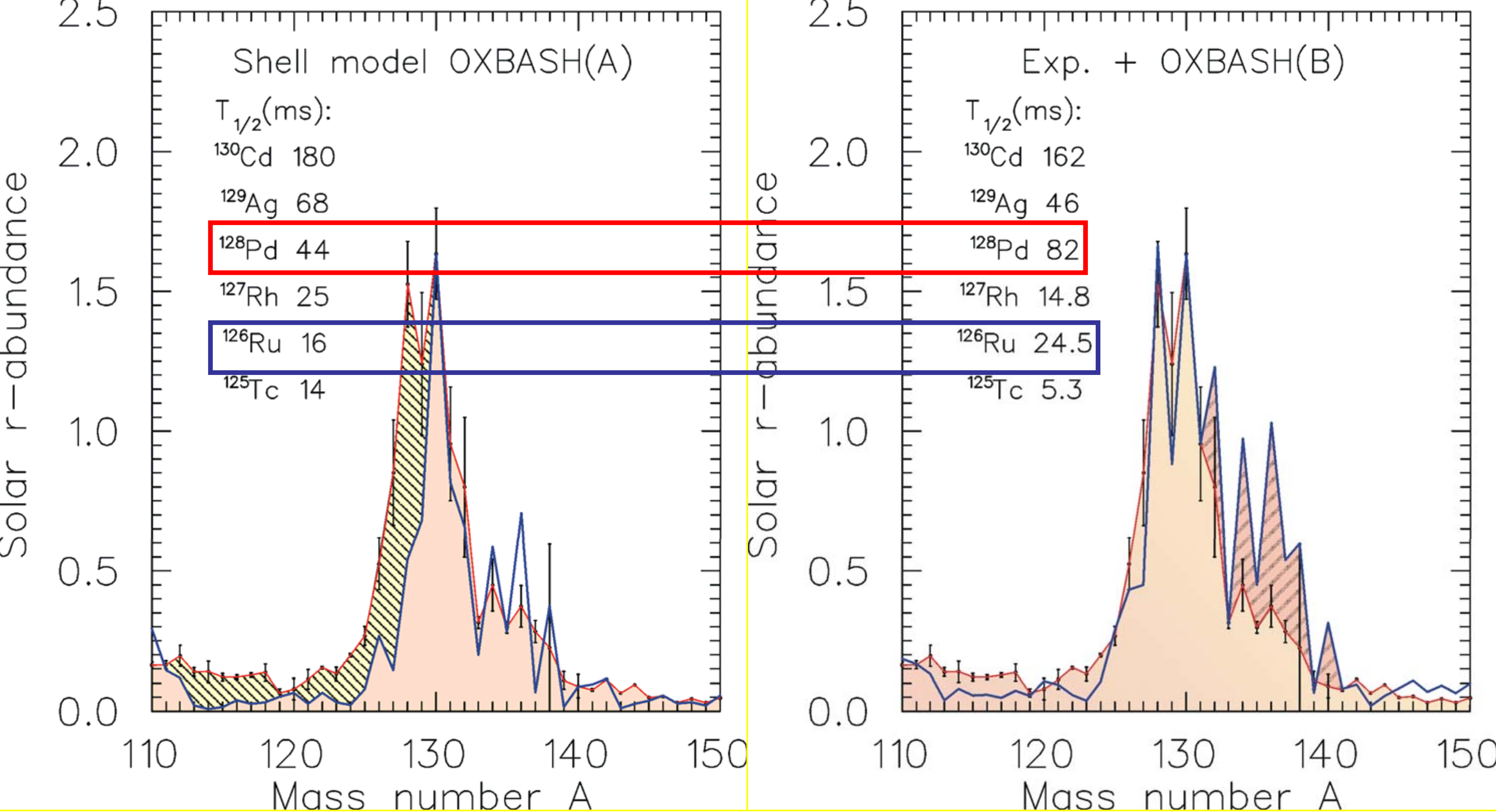
^{134}Sn 1.4 seconds

^{136}Sn 275 milliseconds

^{138}Sn ~150 milliseconds

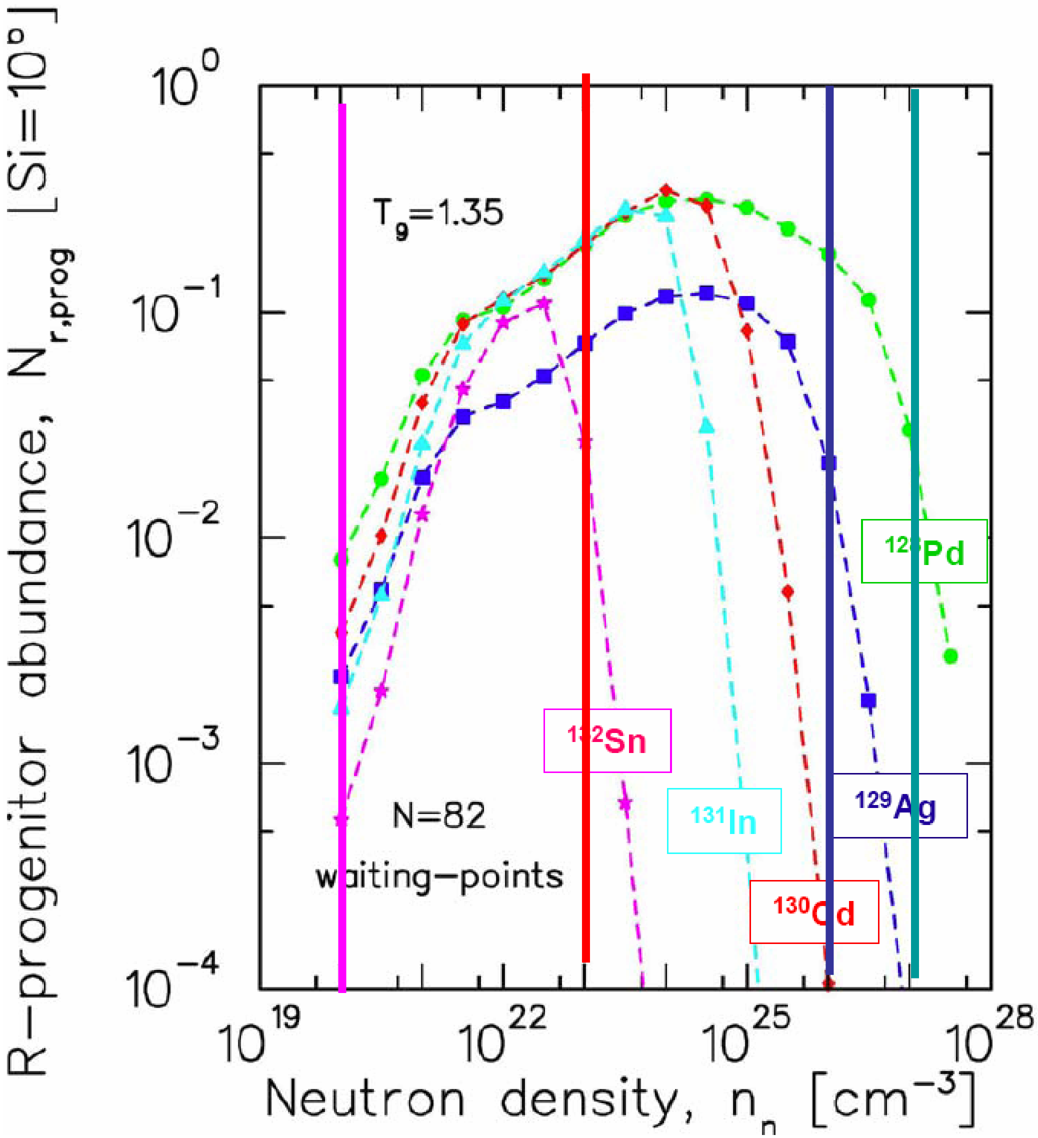
Half life governs two quantities: how much is "waiting around" and, "how long does it take to pass on".

Note the blocking power of ^{132}Sn that would keep material in a "weak r-process" below A = 130.



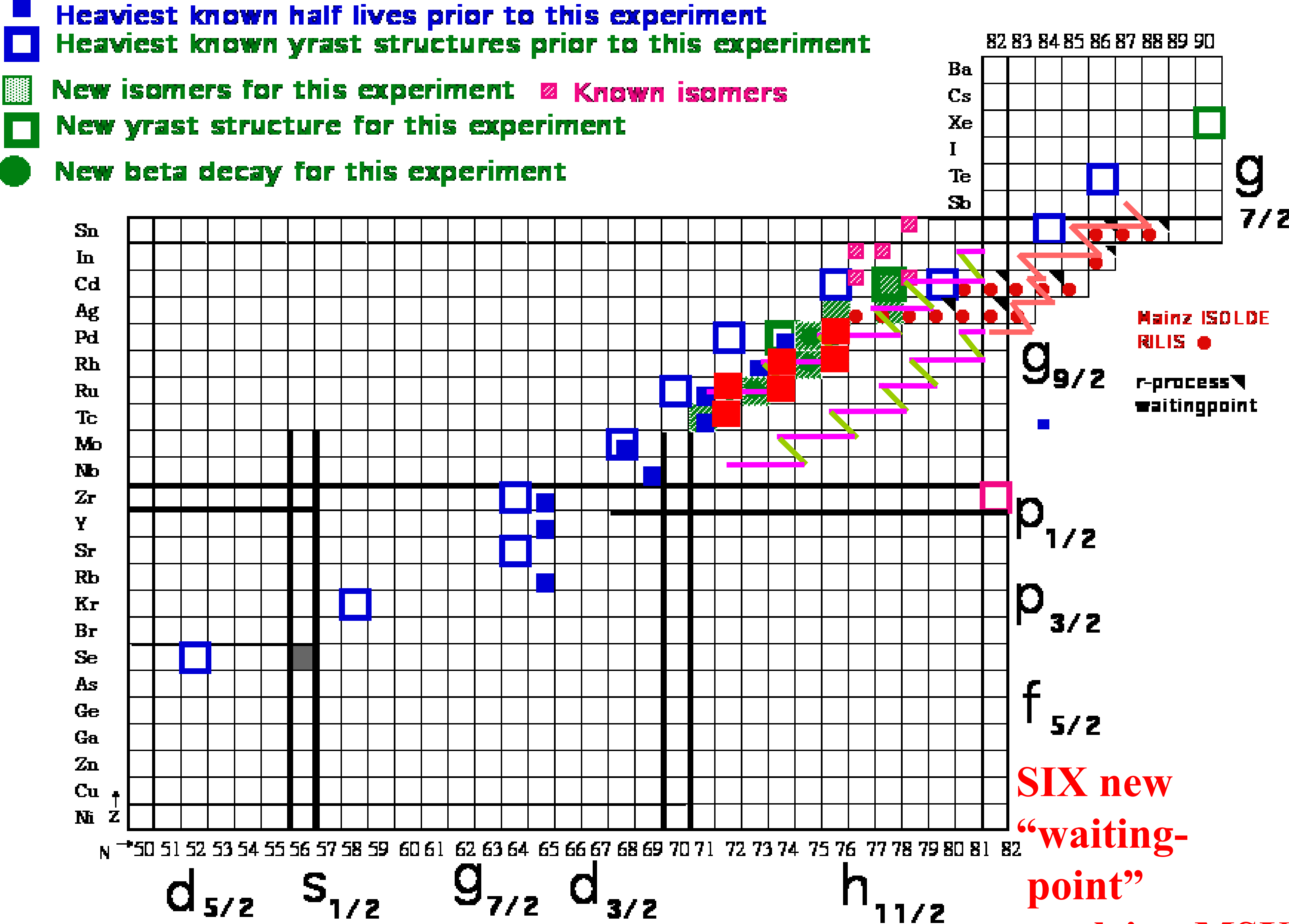
Our data are used in several ways. First is the use of experimental data for the network calculations. Second is to improve models for the many nuclides that have not yet been studied. This is one example.

P. Möller, J. R. Nix, and K.-L. Kratz, ADNDT 66, 131(1997).

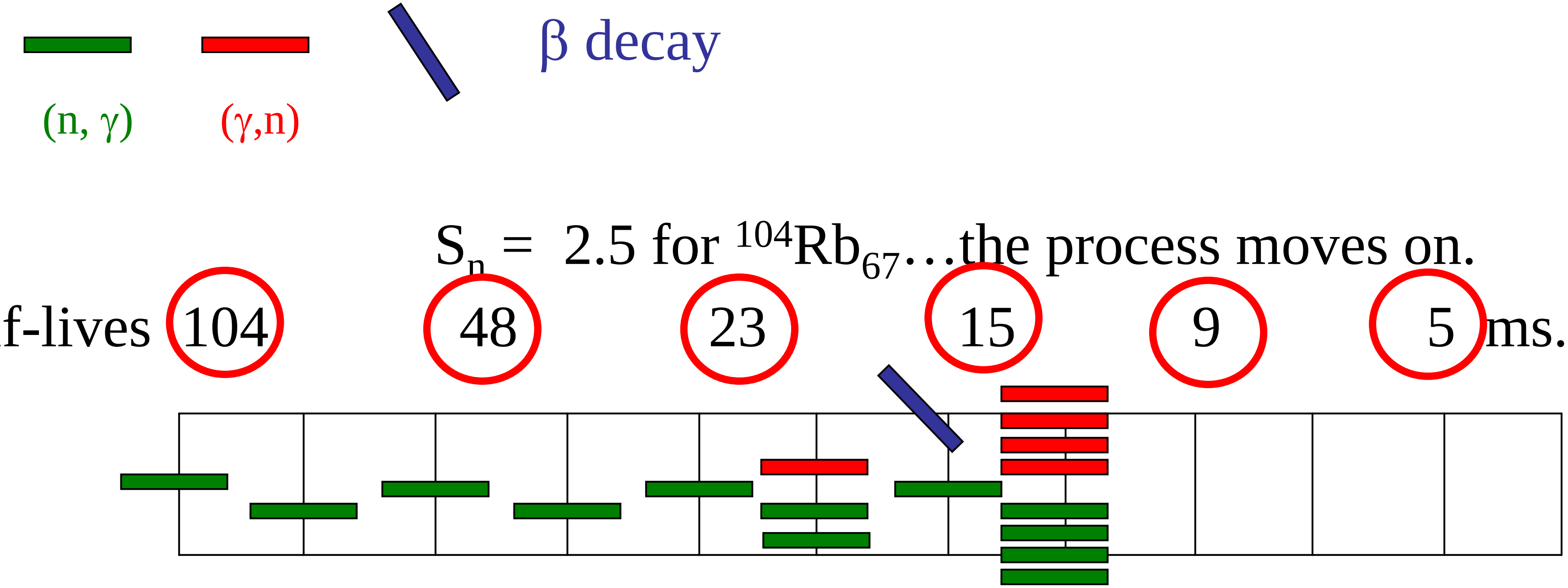


nuclides	N = 82	N = 83	
49 In=131 132	227 6.2	201 2.7	Half life (ms) S_n (MeV)
48 Cd 130 131	165 6.2	68 2.0	S_n (MeV)
47 Ag 129 130	46 5.6	42 2.0	S_n (MeV)
46 Pd 128 129	56 5.5	117 1.5	S_n (MeV)
45 Rh 127 128	22 5	18 1.2	S_n (MeV)
44 Ru 126 127	34 4.9	36 0.7	S_n (MeV)
43 Tc 125 126	9 4.3	8 0.7	S_n (MeV)
42 Mo 124 125	11 4.2	9 0.1	S_n (MeV)
41 Nb 123 124	3.5 3.4	4.1 0.08	S_n (MeV)
40 Zr 122 123	4.3 3.6	3.8 -0.6	Half life (ms) Neutron separatio Energy (MeV) S_n

Summary: Where are we now?



MSU1015: Decay of Rh-120 to levels of Pd-120



S_n =	5.0	2.3	4.5	2.1	4.3	1.9	4.1	1.3	3.4	0.9	2.5
$_{36}$Kr	98	99	100	101	102	103	**104**	105	106	107	108
N =	62	63	64	65	66	67	68	69	70	71	72

A weak r-process can come from:

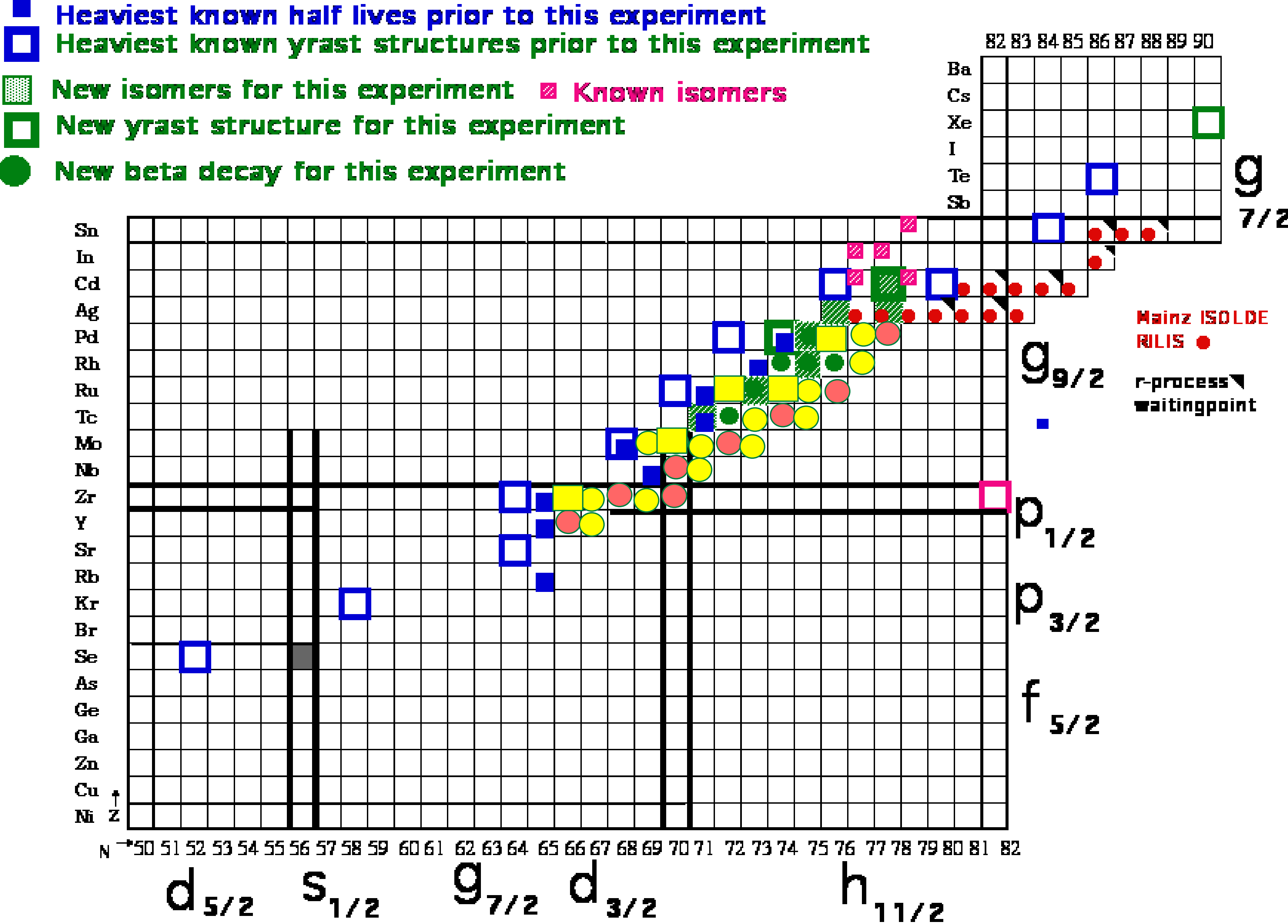
1. Low neutron density….the system just does not move out as far.
2. A high temperature…the system cannot move as far out
3. A short time.

The new MSU data are helpful for the first two.

What would be nice???????

At ISOLDE, targets with shorter release times to probe some of the interesting spectroscopy at these limits. The neutron detector has an efficiency of ~30% and low background. For gamma rays, the efficiency with 5 detectors is about 4%, hence it is possible to obtain half-life data for nuclides, but much less spectroscopy.

At MSU…….another order or so of magnitude in beam current…..



MSU1015: Decay of Rh-120 to levels of Pd-120

Thank you for your attention.

J. Shergur,[1,2] A. Wöhr,[1,3] W. B. Walters,[1] K.-L. Kratz,[4] O. Arndt,[4] B. A. Brown,[5] J. Cederkall,[6] I. Dillmann,[4,7] L. M. Fraile,[6,8] P. Hoff,[9] A. Joinet,[6] U. Köster,[6] B. Pfeiffer,[4] and the ISOLDE Collaboration[6]
[1] *Department of Chemistry, University of Maryland, College Park, Maryland, 20742-2021, USA*
[2] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3] *Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556*
[4] *Institut für Kernchemie, Universität Mainz, D-55128 Mainz, Germany*
[5] *Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321, USA*

J. Shergur,[1] B. A. Brown,[2] V. Fedoseyev,[3] U. Köster,[4] K.-L. Kratz,[5] D. Seweryniak,[1,6] W. B. Walters,[1] A. Wöhr,[1] D. Fedorov,[7] M. Hannawald,[5] M. Hjorth-Jensen,[8] V. Mishin,[3] B. Pfeiffer,[5] J. J. Ressler,[1] H. O. U. Fynbo,[4] P. Hoff,[9] H. Mach,[10] T. Nilsson,[4] K. Wilhelmsen-Rolander,[11] H. Simon,[4] A. Bickley,[1] and the ISOLDE Collaboration[4]
[1] *Department of Chemistry, University of Maryland, College Park, Maryland, 20742-2021*
[2] *Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321*
[3] *Institute of Spectroscopy, Russian Academy of Sciences, RU-142092 Troitsk, Russia*
[4] *Experimental Physics Division, ISOLDE, CERN, CH-1211 Geneva 23, Switzerland*
[5] *Institut für Kernchemie, Universität Mainz, D-55099 Mainz, Germany*
[6] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439*
[7] *Petersburg Nuclear Physics Institute, RAS 188350, Gatchina, Russia*
[8] *Department of Physics, University of Oslo, NO-0316 Oslo, Norway*
[9] *Department of Chemistry, University of Oslo, NO-1163 Oslo, Norway*
[10] *Department of Neutron Research, Uppsala University, S-61182 Nyköping, Sweden*
[11] *Department of Physics, Stockholms Universitet, S-11385 Stockholm, Sweden*

ISOLDE
Sn collaborators

W.B. Walters[1], B.E. Tomlin[2,3], P.F. Mantica[2,3], B.A. Brown[2,4], A.D. Davies[2,4], A. Estrade[4], P.T. Hosmer[2,4], N. Hoteling[1], S.N. Liddick[2,3], T.J. Mertzimekis[2], F. Montes[2,4], A.C. Morton[2], W.F. Mueller[2], M. Ouellette[2,4], E. Pellegrini[4], J. Rikovska Stone[5], P. Santi[2], D. Seweryniak[6], H. Schatz[2,4], and J. Shergur[1]
(1) *Department of Chemistry and Biochemistry, University of Maryland, College Park, MD 20742 USA*
(2) *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824 USA*
(3) *Department of Chemistry, Michigan State University, East Lansing, MI 48824 USA*
(4) *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824 USA*
(5) *Physics Division, Argonne National Laboratory, Argonne, IL 60439 USA and*
(6) *Department of Physics, Oxford University, Oxford, UK OX1 3PU United Kingdom*

MSU Rh
collaborators